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**INTRODUCTION TO THE  
STUDY OF IGNEOUS ROCKS**

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# INTRODUCTION

TO THE

# STUDY OF IGNEOUS ROCKS

BY

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## PREFACE

The plan of the present work is that of selecting from the large body of observed facts bearing on the identification of rocks with the microscope those which it is desirable for the beginner to get command of in the course of his early studies. The work is intended as an introduction to the exhaustive treatises on the subject. Inasmuch as the student invariably begins his laboratory work with the igneous rocks, these alone, with their constituent minerals, have been considered. Such a method of attack at once greatly limits the field on its mineralogical side, and permits of an extended treatment of determinative methods.

In the discussion of the characteristics of a given rock-making mineral the aim has been to impart at the outset the most important diagnostic information regarding it. In the tables for desk use a fairly extended enumeration of the properties of the minerals of igneous rocks is given, but here also emphasis has been laid, by the use of bold face type, upon their more important characteristics from the point of view of the beginner who has to learn to identify them.

The text dealing with the igneous type rocks is devoted entirely to setting forth the assemblages of facts of discriminative significance which are made use of in recognizing them in thin sections. Such a treatment can make no claim to completeness of exposition from the point of view of the geologist. The student will not, however, come to regard rocks merely as objects which can be classified by the recognition of their mineralogy and structures. It is believed that by emphasizing their differences the beginner can most quickly be put in possession of a knowledge of their complexity, and be led to take the interest in them which the petrologist must feel. The difficulties of the student are due

in great part to the largeness of the field of petrography and to the abundance of its literature. The very considerable number of rare varietal rocks, each with its own name, is bewildering to the beginner. The present work does not aim to do more than tabulate them in a way to facilitate the comparison of their mineralogical composition and basic structures.

In the last chapters of the book the precise quantitative classification of rocks proposed by Cross, Iddings, Pirsson and Washington, is briefly outlined. A relatively large amount of space is, however, devoted to acquainting the student with the method of calculating the chemical analyses of rocks, the initial step in making use of the valuable body of chemical data made available by this admirable scheme of classification.

The book presupposes an acquaintance with rocks such as is gained in the first year's work in geology, and such a study of mineralogy as is usually made in a year's course in college. The Miller symbols for crystal planes have been used, and the expanded chemical formulæ of minerals have been retained.

The writer wishes to thank Dr. A. F. Rogers for permission to use Figs. 4 and 7, and to thank Dr. J. P. Iddings for his permission to print the figures in Chapter VIII. The tables for use in the calculation of the norm, pages 194 to 221, have been added with the generous consent of the authors of "The Quantitative Classification of Igneous Rocks."

The writer is desirous of acknowledging his large indebtedness to Dr. A. F. Rogers, to Dr. H. S. Washington and to Dr. J. P. Iddings for their kindly assistance with portions of the manuscript, and for the invaluable help which their published works have given him. He would also acknowledge with gratitude the continued assistance and encouragement extended throughout the whole course of the work to him by Professor J. F. Kemp of Columbia University.

G. I. F.

COLORADO SPRINGS,  
*July, 1913.*

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# INTRODUCTION TO THE STUDY OF IGNEOUS ROCKS

## CHAPTER I

### THE QUALITATIVE CLASSIFICATION OF IGNEOUS ROCKS

Every classification of igneous rocks which is to serve the ends of microscopic study is beset with difficulties, and such a concise statement as is made in the Table of Igneous Rocks on page 98 may readily be misinterpreted by the beginner, or he may fail altogether to understand it. The body of fact to be dealt with is large; its adequate simple expression is not easy; and there is danger that the student may have no sense of the relative values of parts of the subject. It should be understood at the outset that while the microscope is vastly better than the unaided eye for the study of rocks still it does not give us all the information we need for the more refined descriptions. When we do not supplement microscopic study with chemical analysis we are in large part forced to consider rocks qualitatively. The classification of rocks, as made for microscopic work, is therefore qualitative and not quantitative. As such it lacks the precision of the quantitative classification which is considered in Chapter IX. Microscopic work has, however, the advantage of being exceedingly rapid. The trained eye can infer much about the nature of a rock under the microscope almost at a glance. The chemical analysis of a rock, on the other hand, cannot well be made in less than three or four days. Moreover, the ability to make a satisfactory chemical analysis is the fruit of much training. It demands refined skill in manipulation in addition to close acquaintance with special chemical methods. Few can devote themselves to this line of research. At the same time

the great body of facts revealed by the microscope is so important to the student of rocks as to be quite indispensable.

The number of minerals which occur in the igneous rocks is small, not far from 90, as compared with the total number of minerals known. Of the pyrogenetic minerals, *i. e.*, those formed by fusion in igneous rocks, many are very rare; about 25 are of first-rate importance for getting at the nature of an igneous rock under the microscope. The remainder occur sparingly; they are called accessory minerals; and altogether they make up only a very small part of the igneous rocks. They are practically ignored in the assignment of a rock to its place in the classification table. Furthermore, the number of type rocks which, by reason of their frequency, it is desirable to set up in a classification scheme, is small, much less than a score. The student who is familiar with these primary rock types is in a position immediately to understand the place of about 150 other rocks as being in the nature of variations of the main types. He is, moreover, able to read intelligently the literature dealing with rocks. Such a knowledge of the main rock types is serviceable for the mining engineer.

The key statement which appears below is drawn up as an introduction to the table on page 98 at the risk of needless repetition to emphasize in an unmistakable way the considerations on which the qualitative classification of igneous rocks depends.

**GRANITE:** alkali feldspars; mica, amphibole, pyroxene; quartz.

Granitoid texture.

**RHYOLITE:** same minerals as granite.

Groundmass present.

**SYENITE:** alkali feldspars; mica, amphibole, pyroxene.

Granitoid texture.

**TRACHYTE:** same minerals as syenite.

Groundmass present.

**NEPHELITE-SYENITE:** alkali feldspars; mica, amphibole, pyroxene; nephelite.

Granitoid texture.

**PHONOLITE**: same minerals as nephelite-syenite.

Groundmass present.

**QUARTZ-DIORITE**: calci-alkalic feldspars; mica, amphibole; quartz.

Granitoid texture.

**DACITE**: same minerals as quartz-diorite.

Groundmass present.

**DIORITE**: calci-alkalic feldspars; mica, amphibole.

Granitoid texture.

**ANDESITE**: same minerals as diorite.

Groundmass present.

**GABBRO**: calcic feldspars; pyroxene.

Granitoid texture.

**BASALT**: same minerals as gabbro.

Groundmass present.

**DIABASE**: same minerals as gabbro and basalt.

Intermediate in texture between gabbro and basalt.

It appears at once from a study of the key that two considerations are all important. In the first place we need to know what minerals occur in the rock and so give character to it. Were other minerals present instead of a given set the rock would receive another name. In the second place it is clear that different names must be given to rocks which have cooled from the molten state at markedly different rates. Thus in trachyte the same minerals occur as in syenite. Chemically the two rocks may be in all respects alike; but owing to the fact that trachyte cooled with relative rapidity its texture is very different from that of syenite which cooled with extreme slowness. In the case of syenite all of the original molten magma became solid as crystalline minerals of much the same size. The progress of the cooling was sufficiently long continued for this result. At every stage crystals of several minerals were in process of formation at much the same time, and these minerals mutually interfered with each other as they grew. The ragged boundary line between any two crystals is a rough compromise of mutual adjustment.

This characteristic texture finds expression in such rocks as granite, syenite, diorite and gabbro. It has been called the *granitoid texture*. The term *phanerocrystalline*, which expresses the fact that the rock is composed entirely of crystals visible to the unaided eye, is an equally convenient one. On the other hand the case of trachyte, for instance, is radically different. In it only a few crystals can be seen with the unaided eye, and under the microscope the crystals appear of such markedly different sizes as to point to their growth in different "generations." It is known that crystals of certain minerals may grow much more rapidly than crystals of other minerals beside them, but in many instances crystals of one mineral had attained to fairly large size ahead of others and before the lava which contained them left its buried position in the earth to be poured out as a surface flow. After extrusion the uncrystallized portion of the lava may be chilled over its surface by contact with the air, and the whole of its mass cooled rapidly. Only small crystals may have time to form under these conditions. If the cooling be rapid enough some of the rock will cool as a glass, although in such glasses minute crystals have usually had time to grow before the freezing of the rock. (See Fig. 45.) When, therefore, a rock shows notably larger crystals in a web of little crystals, or when, as often happens, some glass appears enmeshing the smaller crystals, individuals of a "second generation," we speak of the rock as having a *groundmass*. The groundmass may be wholly crystalline, or partly crystalline and partly glassy. Much of the rock appears stony and non-crystalline to the unaided eye. The term *aphanitic* is employed to indicate this condition. The distinction as to texture between *phanerocrystalline* and *aphanitic* is easily made. Extrusive and intrusive lavas and dikes are characterized by the presence of a groundmass. Those rocks which cooled so slowly while deeply buried in the earth as to have had all of their substance arranged in crystals of the same general time of growth have no groundmass. They are the *granitoid textured rocks*. It should be noted that all variations in

texture exist from the granitoid texture with no groundmass to that which is wholly glassy. None the less the significant difference in texture between the granitoid rocks and those having a groundmass, depending as it does upon striking differences in geological occurrence, is properly given fundamental weight in the qualitative classification.

When the above considerations are borne in mind the table of igneous rocks as drawn up on page 2 may be much simplified in its expression. It is at once noted that six of the rock types carry the same kind of feldspar, alkali feldspar, while seven other rock types may be distinguished from the alkali feldspar rocks by reason of the fact that their feldspathic constituent is chemically different as being calci-alkalic, or calcic, *i.e.*, lime-soda feldspar. Feldspar of one or the other kind is very abundant in nearly all igneous rocks. Rarer rock types are met, pyroxenite, peridotite, augitite and limburgite, which are almost or wholly lacking in feldspar. The classification takes account in the first place, then, of the character of the feldspar in the rock. The alkali feldspars are represented in the minerals orthoclase, microcline, albite, microperthite, soda-orthoclase and soda-microcline. These six minerals are aluminous silicates of the alkalis,  $K_2O$  and  $Na_2O$ . The lime-soda feldspars are chemically isomorphous mixtures of the albite molecule,  $Na_2O \cdot Al_2O_3 \cdot 6SiO_2$  with the molecule  $CaO \cdot Al_2O_3 \cdot 2SiO_2$ . This occurs pure in the feldspar anorthite, so that the lime-soda feldspars are those members of the plagioclase series which contain mixtures of the albite and anorthite molecules.

The six types of igneous rock which are characterized by the presence of the alkali feldspars carry in addition to the feldspathic constituents the dark colored silicates mica, amphibole and pyroxene. Any one, any two, or all three may be represented in the alkali feldspar rocks, but no account is taken of them in making further subdivisions. On the other hand the case of the lime-soda feldspar rocks is such that with calci-alkalic feldspar we are apt to have preponderant mica and amphibole, while the

calcic feldspar rocks carry pyroxene as the preponderant dark silicate. Further subdivisions are made in the case of the alkali feldspar rocks on the basis of the occurrence or absence of quartz, nephelite and leucite. It is found that many rocks which carry nephelite have leucite in them as well. Other rocks are characterized by the presence of nephelite, and leucite is absent. But it is a rule that if either nephelite or leucite is present in a rock quartz will not be found in it. If on the other hand quartz is present in a rock we shall never find either nephelite or leucite in it. The cause back of this fact lies in the chemical composition of the molten magmas. When either nephelite or leucite crystallizes out of a molten magma it is invariably found on chemical analysis that the magma was too poor in silica for quartz to form in it. In like manner the rocks of the calci-alkalic feldspar division are subdivided on the basis of the occurrence or absence of quartz.

The student needs to hold in mind all the while that the classification scheme takes account of texture as well as of mineralogical character. Thus alkali feldspars and dark silicates of the mica, amphibole and pyroxene series are met in trachyte, but the rock is called trachyte for the reason that it is also characterized by having a groundmass. It is aphanitic. Syenite has the same minerals as trachyte but it shows the granitoid phanerocrystalline texture. Granite differs from syenite in that it contains quartz. Like syenite, nephelite-syenite is phanerocrystalline, but it carries nephelite in addition to the constituents of syenite. In the same way, crudely stated, rhyolite is trachyte with quartz added, and dacite is andesite with quartz added. Such a statement is, however, misleading for the reason that a typical trachyte is in large measure different chemically from a typical rhyolite. The chemical composition of the magma stamps itself all through the web of the rock in the appearance of the several minerals and the groundmass.

It is believed that with the above explanations in mind the beginner will readily understand the expanded form of the table

of igneous rocks on page 98. As a presentation of important rock types it will in some form or other persist indefinitely. The student should become thoroughly familiar with it. Its principal defect is that it is not quantitative. For instance we may feel safe in calling a granite which has some such percentage of quartz as 30 per cent. by the name granite, but shall we also call the rock granite if it have only 2 per cent. of quartz? Or is such a rock to be called syenite? The study of rocks has made it clear that all possible gradations in mineral percentages exist between types. Herein lies the great value of a precise quantitative classification, however much work must precede the placing of a rock where it belongs in it. Again all gradations exist in the texture of rocks. The gabbro-diorite-basalt series will serve to illustrate this. These rocks are composed essentially of calcic feldspar and pyroxene. Typical diorite is midway in texture between gabbro and basalt. The magma from which any one of these three rocks may come is basic, that is, relatively low in silica, but with abundant iron, magnesia and lime. Correlated with this chemical composition is a condition in the molten state of ready fluency. It is found that only with difficulty can the magma be chilled so suddenly as not to permit of the growth of good crystals. It may therefore be represented under different conditions of cooling by an unusually wide range of textures. Analogous cases occur all along the line, and such rocks of intermediate texture are commonly referred to as granite-porphyry, diorite-porphyry, etc. It seems best, however, to consider them as variants from the main types, and not to add them to the tabular statement.

Inasmuch as the thin section of a rock to be examined under the microscope cuts across individual minerals in a haphazard way some individuals will happen to be so sliced as to present more evidence for their identification than others not so fortunately cut. In any one rock slide we usually have many individual crystals of the same mineral. We look the field over for the most favorable individuals and work on these first.



The safe determination of one of them throws light on the others which resemble it so closely as to be distinct in appearance from the sections of other minerals. The ability to select favorable pieces for study is conditioned by a knowledge of the means to be applied in determining the several minerals. In practice we soon become able to recognize many minerals almost at sight, and long experience helps us to make a very shrewd guess in almost every case. This, however, is not enough. We are in the end called upon to apply such tests as may make our determinations certain. To use the microscope in this work intelligently we must have clear ideas as to the nature of light movement in crystals, and a sure knowledge of a number of tests of which constant use is to be made. Chapter III deals with the movement of light in crystals, and in general terms with determinative methods. In later chapters where the rock-making minerals are severally described constant reference is made to the discussions in Chapter III.

## CHAPTER II

### THE DETERMINATION OF THE IGNEOUS ROCKS IN HAND SPECIMENS

The possibility of identifying an igneous rock with the unaided eye or with a hand lens is so limited that the most we can do even with considerable experience is to make a shrewd guess as to what the rock really is. We can make only approximate identifications of a few minerals. We can, however, very readily separate the rocks with a groundmass from those which are phanero-crystalline and show the granitoid texture. We can recognize the siliceous character of some rocks, we can make out the basic nature of others, and we can assign others to a half-way position between the siliceous and the basic members of the series of type rocks. We are aided in judging rightly by knowing that certain rocks are very common and others are rare. A simplified table of rocks for use in the field is given below. Rocks which are common are in bold face type, rare rocks are printed in plain type and the constituent minerals are in *Italics*.

Having noted the presence or absence of a groundmass we try to make out the character of the feldspar. Pink feldspar may be assigned to orthoclase or microcline. Feldspar which shows Carlsbad twinning is probably orthoclase or microcline. As the rock is held in the sunlight one part of the twin will flash brightly while the other part looks dull, and when the rock is held in another position these effects are reversed. In the orthoclase-microcline rocks we note black minerals and these may be biotite, hornblende or augite. We can tell biotite by its flashing black surface and because we can cleave it with the point of a knife. It is soft as well. Hornblende and augite, which are hard and not readily cleavable, cannot be told apart unless they come in

	Orthoclase Microcline			Plagioclase		
	Biotite Hornblende Augite			Biotite Hornblende		
	Quartz		Nephelite Leucite	Quartz		Olivine
Lavas: A groundmass is present.	RHYOLITE	Trachyte	Phonolite	Dacite	ANDESITE	OL.-BASALT
						BASALT
						OL.-DIABASE
Granitoid Texture: No groundmass present.	GRANITE	Syenite	Neph.-syenite	Q.-DIORITE	DIORITE	OL.-GABBRO
						GABBRO

good crystals large enough for us to make out the six-sided cross-section of hornblende or the eight-sided cross-section of augite. (See Figs. 34 and 35.) Quartz is recognized by reason of its being clear and glassy. We see through it although it may look dark because it has a dark background. The feldspars on the other hand are not clearly transparent but porcelain-like. We may tell leucite by its icositetrahedral form, but in no other way. Nephelite may cause the rock to look greasy but we can never identify it safely. If the rock contains quartz it will not contain either leucite or nephelite. If the rock carries leucite, nephelite is apt to be present, but quartz will not be present.

Plagioclase feldspar is often white, or gray, or bluish-gray with flashing blue light effects. Its albite twinning may cause its surface to appear striated. We try to make out the striations with a lens, examining several pieces. When the plagioclase-bearing rock contains black crystals some of which are plainly biotite (recognized by its cleavage), we may infer that the indeterminate black mineral with the biotite is hornblende rather than augite. When on the other hand the black mineral is all of a kind and not biotite, and the rock containing it is plainly basic, *i.e.*, of dark color, and having a dull, stony, non-glassy appearance, we may with some safety call the black mineral augite. Olivine in blackish basic lavas may occur in clear glassy greenish-yellow grains. We are seldom able to determine this mineral with security in other rocks.

If we can make out this much of the mineralogy of rocks it is a very great help, but often we cannot identify the particular variety of feldspar, nor can we see quartz. We judge then by the color of the rock, and by its appearance, whether siliceous or basic or halfway between the two.

Thus, in working with the lavas which show a groundmass, when we see quartz we conclude that the rock is either rhyolite or dacite. It is probably rhyolite because this rock is very common, and dacite is rare. We may be able to make out the character of the feldspar. Rhyolite can often be known, even

when we cannot see either quartz or feldspar in it, by its siliceous glassy character. It may be extremely glassy so that it breaks under the hammer much like artificial glass. The color of rhyolite may be jet black (suggesting the basic rock basalt) or reddish or greenish, but we hold safely in all cases to its siliceous nature. Usually if a lava is black and not glassy, but evidently basic and "stony" it is basalt. If we see olivine in such a lava we call it olivine-basalt. If the lava is not rhyolite, nor basalt, it may be trachyte, phonolite or andesite. Andesite is very common and the other rocks among these three are rare. We guess andesite if the rock is medium dark and appears to be halfway between the siliceous and basic ends of the lava series. If we can make out plagioclase and biotite the determination is much more certain, but we will never refer a rock to trachyte instead of andesite unless we can clearly see Carlsbad twinning on its feldspar. If we see leucite we conclude safely that the rock should be put with the phonolites but otherwise we have no good reason for such a determination.

When we are working with the granitoid rocks the presence of quartz usually means that the rock is the very common rock granite, and not quartz-diorite, which is much rarer. We can usually prove the feldspar, orthoclase or microcline, by its Carlsbad twinning. If we can detect orthoclase in a granitoid rock in which there is no quartz the rock may be either syenite or nephelite-syenite, we cannot say which. We guess syenite because this rock is the commoner of the two. If we cannot make out the character of the feldspar the rock may be syenite, nephelite-syenite, or diorite; we cannot safely say which one it is. Diorite should be darker than the others, and it is more common. We may determine plagioclase and so establish the position of the rock, judging that it is not basic enough for gabbro. Gabbro on the other hand is plainly basic and generally dark. Again in gabbro we can many times clearly make out the striations on plagioclase feldspar by examining a number of pieces. Labradorite feldspar will often show striations, and it

may also be known by its flashing blue-gray or dark drab color.

Diabase is recognized by its very even medium grain, its dark pepper and salt color, and its basic character. With a lens we may make out something of its peculiar structure, white plagioclase intimately grown together with augite crystals which have less individuality than the feldspar. The augite was formed last in such a manner as to fill the interspaces between the feldspars.

The student will have no difficulty in the field in telling the igneous rocks from members of the two other great classes of rocks—the sedimentary and metamorphic rocks. Members of the igneous series are homogeneous and their substance is all of a kind. Sedimentary rocks are in beds and layers as originally deposited under water. Sand grains, consisting of quartz, feldspar and the dark silicates, when they are consolidated, make ordinary sandstone. Some sandstones are made up almost entirely of quartz grains. Gravel consolidated makes conglomerate. Shale is the rock resulting from the consolidation of layers of mud. Limestone is formed of calcareous remains, limy shell fragments. This rock effervesces readily with HCl.

The metamorphic rocks are laminated or foliated. To make them sedimentary or igneous original rocks have been worked over by heat, pressure or chemical means. The metamorphic product has a distinct grain as compared with an igneous rock but it will not show such definite clear-cut parallel banding as appears in the sedimentary rocks. Pure quartz sandstone after metamorphism and induration is quartzite. Limestone is in the same manner changed to marble. Shale slightly metamorphosed becomes slate. Metamorphism carried further results in schist. Granite or conglomerate metamorphosed comes to be gneiss. Gneiss is often rich in feldspar and poor in the dark constituents, mica or hornblende. Schist on the other hand may be poor in feldspar and rich in mica or hornblende. Both rocks contain quartz, and they may be in various instances the meta-

morphosed equivalents of a considerable number of sedimentary and igneous rocks. Gneiss is a metamorphic rock with distinct lamination and the mineralogy of a rock in the igneous granitoid series. Schist is a foliated metamorphic rock which will split into thin slabs or flakes much more readily than gneiss does. We get much more information in the field, where a large amount of a given rock lies before us, as to whether it is a sedimentary or a metamorphic rock, than we do from the study of a single slide under the microscope. Often in a thin section we can see only a little of the structure so apparent in a ledge; but we can with precision determine the mineralogical constituents of the rock. In the metamorphic rocks a very long series of minerals is represented. These cannot be dealt with in the present work, the object of which is to treat only of the igneous rocks and their minerals.

## CHAPTER III

### THE MOVEMENT OF LIGHT IN CRYSTALS

**Nature of Light Transmission.**—Light is transmitted by vibrations in the ether. The vibrations of the luminiferous ether take place in the plane normal to the direction of the advance of the light. For the direction along which light advances the term **ray** is used.

The vibrations by which light is transmitted through a mineral in a rock section lying on the stage of the microscope are vibrations in the plane of the section, *i.e.*, parallel to the plane of the stage, for the reason that normally incident rays coming from below to the section are used. Sound waves are different from light waves in that the air particles move forward and back along the line followed by the sound wave itself.

In the case of white light coming to us from the sun the vibration circuit of any given particle of the ether is believed to be an ellipse which is constantly shifting its position in the plane normal to the ray. With plane polarized light commonly employed in determining minerals the case is different from that of ordinary light. In **plane polarized light** the ether particles are believed to trace straight lines in a single plane forward and back across the ray path.

#### Illustrations of the Nature of Plane Polarized Light

Some realization of the nature of the wave motion in the case of plane polarized light may be gained in the following way. Draw a line across the middle of the page from top to bottom to mark the light path. Then at right angles to this line move the pencil point back and forth, carrying it an equal



distance away on one side of the line and on the other, with the same kind of variation in speed observed in the motion of a pendulum. The pencil point is to move fastest when it crosses the ray path line and to move on either side of this line more and more slowly to the end of its swing, where it is momentarily at rest before its return. The distance traced on either side of the ray path line gives the measure of the amplitude of the vibration. The intensity of the light is proportional to the square of the amplitude. Consider motion of the pencil along the vibration line to the right of the ray path line plus, and motion to the left minus. The period of the vibration may be defined as the time required to trace the circuit of the vibration line forward and back to the point of starting. By the phase is meant a fraction of the time required for a circuit. We may



FIG. 1.

call motion to the right of the ray path line the plus phase, and motion to the left the minus phase. Now to complete the illustration let the paper be like a machine-belt moving along the line drawn for the ray path toward the observer. The tracing made by the pencil will then be a wave form or harmonic curve (Fig. 1). The distance from crest to crest or from trough to trough is a wave length, designated by the Greek letter  $\lambda$ . The wave length for red light is .00076 mm.; for violet light the wave length,  $\lambda$ , is .00038 mm. Light of different colors has different wave lengths, and since light of different colors travels through space with the same velocity, the vibration periods must be unlike for light of different colors. Violet light for instance vibrates twice as rapidly as red light. White light is composite light embracing colored light of every wave length in the spectrum.

To bring more clearly to mind the nature of plane polarized light the following illustration is useful. When a rope is made fast at one end to a wall and the free end is moved rapidly up and down by the hand in a line normal to the ground, wave motion is set up in the rope and the vibration of particles in the

rope is in a plane perpendicular to the ground. Suppose now that a slot be cut in a board proportioned to the thickness of the rope and to the amplitude of the motion. The rope will then move freely up and down in the slot when its plane of vibration is parallel to the slot, but motion in the rope will be stopped completely when the slot is at right angles to the plane of vibration of the rope. It is important to note that when the slot is held at any acute angle to the plane of vibration of the rope some slight component of the total vibration will get through. More will get through the more nearly the slot and the plane of vibration of the rope approach each other.

The Nicol prism, or nicol, placed beneath the stage of the microscope is an apparatus for producing plane polarized light. Its construction is described on page 21. Plane polarized light cannot be recognized as such by the unaided eye. The vibration direction of the light which the nicol yields should be marked upon it, and the nicol may be so set that this vibration direction is parallel with the N. S. cross-hair. (It will be convenient to refer to the cross-hairs as the N. S. and E. W. cross-hairs, as suggested by the directions on a map.) We need to make sure of the vibration direction of the nicol below the stage. A simple means of finding the vibration direction consists in placing on the stage of the microscope a section of biotite in which the cleavage lines running parallel to each other are observable. As the mineral is turned on the stage it will be found to absorb the light strongly, and in consequence to be much darker, when its cleavage lines are parallel with the vibration direction of the nicol.

A principle of the utmost importance in the behavior of light is the principle of **refraction**. When light passes for instance from air into a glass plate its velocity is less than it was in air and the ray is bent aside from its course or refracted. We define the **index of refraction** (denoted by  $n$ ), of the glass, as the ratio between the velocities of light in the two media. Air is commonly taken as the standard of comparison. Let Fig. 2

represent a section of a glass plate in air. It can be proved that the sine of the angle of incidence,  $I$ , measured from the normal to the plate, bears a constant ratio to the sine of the angle of refraction,  $R$ .

$$\frac{\text{Sine } I}{\text{Sine } R} = n$$

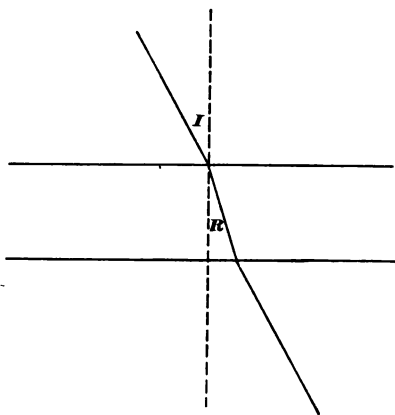


FIG. 2.

The ray in going from a rarer into a denser medium is bent toward the normal. In passing from a denser into a rarer medium it is bent away from the normal. The value of  $n$  changes for light of different colors, that is, for light of different wave lengths. Furthermore, the reciprocal of  $n$ , that is,  $\frac{1}{n}$ , gives the velocity of the light in the denser medium as compared with its velocity in air.

Those minerals which have high values for  $n$  (1.600 or more), stand out boldly in rock sections. Their outlines are clearly marked against other minerals and their surface is rough. This circumstance helps in their recognition. Thus olivine (1.671), epidote (1.751), titanite (1.938), apatite (1.637), calcite (1.601), garnet (1.745–1.873), zircon (1.952), tourmaline (1.650), corundum (1.766), the amphiboles and the pyroxenes, with high values for  $n$ , make a striking appearance in thin sections beside the feldspars (1.522–1.594), nephelite (1.540), or quartz (1.550), which have values for  $n$  much nearer that of Canada balsam. When the feldspars, with or without quartz, make up a large part of the rock, the difference between  $n$  for them and the other

minerals mentioned above is so great as to give the minerals with  $n$  very high a striking appearance of relief in the section.

### Becke Test for Value of Index of Refraction

When two minerals side by side in a section on the stage of the microscope have a vertical bounding wall between them<sup>1</sup> it is possible with great ease to make out slight differences in their indices of refraction. Focus with the high power objective on the line between them using ordinary light. Raise the objective and a thin line of white light will be seen to make its way into the mineral having the higher index of refraction. This is known as the Becke test.

In isometric crystals, as in amorphous bodies and fluids, there is no double refraction, whatever the direction of light transmission. They are called isotropic media. In tetragonal and hexagonal crystals, as will be shown below, there is double refraction for every direction of transmission excepting one direction, that of the crystal axis  $c$ . This direction in tetragonal and hexagonal crystals is the direction of the single optic axis. The optic axis, it should be noted, is a direction, not a line fixed in one place in a crystal. In orthorhombic, monoclinic and triclinic crystals there is double refraction for every direction of transmission excepting two, the directions of the two optic axes.

### Velocity of Light in Various Directions in Crystals Not the Same

By far the most important single fact to hold in mind regarding the optical behavior of crystals is this: that, with the exception of isometric crystals, light in passing through them moves with unequal velocities in different directions. In orthorhombic, monoclinic, and triclinic crystals, which, optically, form a class by themselves, there are three directions at right angles to each other (called  $Z$ ,  $Y$ , and  $X$ ), along which light moves with maxi-

<sup>1</sup> We can tell that the bounding wall between the two minerals is vertical by shifting the focus on it and seeing that it remains fixed in its place.

imum, intermediate, and minimum velocities. These velocities are the reciprocals of the indices of refraction for light transmission in the three directions *X*, *Y* and *Z*. In the description of minerals not only are these three indices of refraction given, but great care is taken to set forth by diagrams and figures the relation between the light transmission directions corresponding to them and the crystallographic axes. This is the statement of the optical orientation. The measurement of extinction angles, to be considered later on page 36, on which many determinations depend, has to do directly with the optical orientation of the crystal.

The movement of light in such crystal systems as are mentioned above is highly complex. The movement of light in tetragonal and hexagonal crystals which, optically, fall into another class is much less complex. In their case two directions only need be considered, a direction of maximum velocity with a corresponding minimum index of refraction, and a direction at right angles to the first direction for rays traveling with minimum velocity. The index of refraction for this second direction has the highest value for light transmission in such crystals. Light rays which travel rapidly may be thought of as having opposed to them smaller indices of refraction than those which travel slowly. In the description of minerals of this class the values for the maximum and minimum indices of refraction are given. One of these is for the direction of the crystal axis *c*, while the other is for directions at right angles to it. The optical behavior is related to a single axis called the optic axis. This is the same direction as that of the *c* axis. It may be the direction of maximum velocity with the direction of minimum velocity at right angles to it, or *vice versa*.

Light transmission in the remaining class, that of the isometric crystals is simple. In them light moves with equal ease or velocity in all directions. The ray entering a plate of garnet, for instance, at an angle will be bent aside or refracted but it will not be broken up. The isometric minerals are called singly refracting. All other minerals possess the peculiar prop-

erty of splitting up a ray which enters them. After its entrance the ray travels as two rays. This is the phenomenon of **double refraction** and the appearance of crystal plates under the microscope is intimately bound up with it. Double refraction or birefringence is conveniently shown by the behavior of the mineral calcite.

### Double Refraction. Behavior of Calcite, a Doubly Refracting Mineral

Let a fairly thick rhombohedral cleavage fragment of transparent calcite be placed over a pin-hole in a card. Two images of the pinhole will be seen, and as the calcite is turned on  $ro$ , (see Fig. 3), as an axis the image at  $E$  revolves about that at  $O$ , which remains stationary. The ray of white light has been broken into two rays, an extraordinary ray  $E$ , and an ordinary ray  $O$ , which comes straight through. The extraordinary ray has been bent aside or refracted. It has been found that the vibration direction in the calcite plate of the extraordinary ray,  $E$ , the direction of the shorter diagonal of the rhombohedral cleavage piece, is at right angles to the vibration direction of the ordinary ray,  $O$ . Furthermore it has been found by experiment that  $E$  and  $O$  are both rays of plane polarized light.

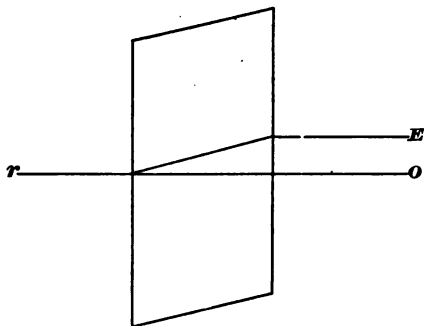


FIG. 3.

**Construction of the Nicol Prism.**—Perfectly transparent calcite is used in the construction of the Nicol prism. A rhombohedral cleavage piece, as in Fig. 4, is trimmed at the ends after the manner indicated by the dotted lines, and then cut

diagonally across so that the cutting plane is at right angles to the shorter diameter of the rhomb, and at about  $93^\circ$  to the cleavage plane trimmed away slightly in the first place. When

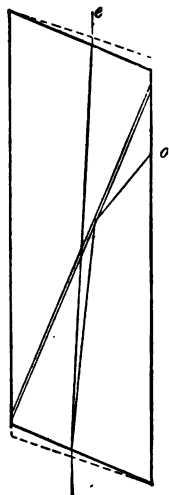
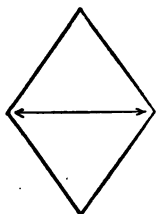


FIG. 4.—Horizontal (above), and vertical cross-sections of the Nicol prism.

the two parts have been polished they are cemented together in the original position with Canada balsam. A ray of light entering the prism from below is broken into ordinary and extraordinary rays, each of which is bent aside. The ordinary ray strikes the Canada balsam at such an angle that it does not pass through it for the reason that it is reflected from the surface of the Canada balsam against the blackened side of the prism and lost. The extraordinary ray alone is able to come through. Its vibration direction as it emerges is that of the shorter diagonal of the rhomb.

The Nicol prism set below the stage is known as the polarizer. Another nicol, the analyzer, is so fixed above the stage that it may readily be made to slide into or out of the tube of the microscope. When it is in play, with its vibration direction at right angles to the vibration direction of the lower nicol, the nicols are said to be crossed.

The difference in the movement of light between an isometric crystal and calcite, a typical doubly refracting mineral is this. Let light originate from a point within an isometric mineral. Ordinary rays will move out in all directions a certain distance in a given time.

There will be no extraordinary rays. The wave surface<sup>1</sup> will be the surface of a sphere.

On the other hand let light originate from a point within a crystal of calcite. Since the mineral is doubly refracting

<sup>1</sup> I. e., the illuminated portion of the crystal.

both extraordinary and ordinary rays will move out in all directions with such velocities that in a given time the wave surface for the ordinary rays will be the surface of a sphere, and the wave surface for the extraordinary rays will be the surface of an ellipsoid of rotation lying wholly outside the spherical wave surface of the ordinary rays; crudely put, a ball inside an egg. Along one direction only, and this is the direction of the optic axis, both ordinary and extraordinary rays will move with equal velocities. For calcite the optic axis is at the same time a diameter of the spherical wave surface for the ordinary rays and the axis about which the ellipse must be rotated to make the wave surface for the extraordinary rays. The optic axis is also the direction of  $c$ , the crystallographic axis.

When the index of refraction for light traveling in a certain direction is given we have a measure of the velocity of the light since it is proportional to  $\frac{1}{n}$ . In tetragonal and in hexagonal crystals it is found that the indices of refraction for extraordinary rays traveling in all possible directions are radii vectores of an ellipse whose major and minor axes are proportioned to the maximum and minimum indices of refraction in the crystal. By the construction of such an elliptical section of the wave surface of a hexagonal or tetragonal crystal we are able to prepare a figure by which we can determine graphically the vibration direction and index of refraction for any direction of light transmission in the crystal.

### Graphical Determination of the Vibration Direction and Index of Refraction

Given the values for  $\omega$ , the index of refraction for the ordinary ray, and  $\epsilon$ , the index of refraction for the extraordinary ray where  $\omega > \epsilon$ , let the ellipse be so constructed that its longer axis equals  $\omega$  and its lesser axis equals  $\epsilon$  (Fig. 5). Draw on  $AA'$  as diameter the circle  $ABA'B'$ . If now the ellipse and circle be



rotated about  $AA'$  as an axis the resultant spherical surface will represent the wave surface for the ordinary rays, and the surface of the ellipsoid of rotation the wave surface for the extraordinary rays. Draw the line  $NN'$  anywhere through the center of the ellipsoid of rotation whose axes are as has been said proportional to the major and minor indices of refraction for the mineral in question. Let  $PP'$  be the plane tangent to the ellipsoid and also parallel to  $NN'$ .

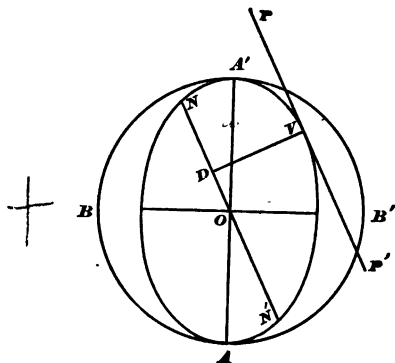


FIG. 5.—Graphical determination of the vibration direction and velocity of a ray traveling along  $NN$  through a tetragonal or hexagonal crystal.

Then  $VD$  the normal to the tangent plane  $PP'$  will be perpendicular at the same time to  $NN'$ .  $VD$  is the vibration direction of the extraordinary ray traveling along  $NN'$ , and for this ray it gives graphically a measure of the index of refraction intermediate between the values  $\omega$  and  $\epsilon$ . The velocity of the ray traveling along  $NN' = \frac{1}{VD}$ . Tetragonal and hexagonal

crystals in which the velocity of the ordinary ray equals the velocity of the fastest of the extraordinary rays are optically positive. When, however, the velocity of the ordinary ray only equals the velocity of the slowest of the extraordinary rays the wave surface figure is different from that constructed above in that the sphere is entirely inside of the ellipsoid of rotation. Such crystals are optically negative. Given the basal section, recognized by the fact that it is dark between crossed nicols, it is easy to determine the + or - optical character of the mineral. The optical figure obtained from the basal section with convergent light is used for this determination. (See page 31.) The determination may be made on any other section provided that the trace of the  $c$  axis is known. (See page 30.)

### Directions of Vibration of Extraordinary and Ordinary Rays in Sections of Tetragonal and Hexagonal Crystals

It has been found that for any direction of transmission in tetragonal and hexagonal crystals there are two vibration directions in the plane normal to the ray. That for the extraordinary ray is at the same time in the plane passed through the ray and the optic axis, while that for the ordinary ray lies in the plane perpendicular to the plane of the ray and the optic axis. This means that when a plate of a tetragonal or hexagonal crystal cut at some angle other than  $90^\circ$  to the *c* axis (*i.e.*, any section except the basal section), lies on the stage of the microscope there are two vibration directions in it perpendicular to the normally incident ray from below. The trace of the optic axis on the section plane defines the vibration direction of the extraordinary ray, and the vibration direction of the ordinary ray is at right angles to this line. These two vibration directions are very easily determined with crossed nicols, for when the section is turned until darkness results then the two vibration directions in the mineral are lined up with the cross-hairs (the vibration directions of the nicols). It is as though in the experiment outlined on page 16 we had, to represent one nicol, a rope with a vertical vibration direction which encounters a slot that is horizontal so that none of the wave motion gets through; and, at the same time, and along the same wave path, we had, to represent the second nicol, another rope with a horizontal vibration direction which encounters a slot vertically across its path so that all wave motion is stopped.

**Explanation of Colored Light Between Crossed Nicols.**—As soon, however, as the section is turned from this position the vibration directions in the mineral section no longer coincide with the vibration directions of the nicols and we get crossed nicol light of some definite color. It increases in intensity until the vibration directions in the mineral section are turned  $45^\circ$  away from the vibration directions of the nicols. From this

point on the light loses intensity as the section is turned until the next extinction position is reached at  $90^\circ$  from the first. There are four such positions of extinction in  $360^\circ$ . The explanation of the occurrence of colored light may be understood by the help of Fig. 6. Plane polarized light, not distinguishable as such by the eye alone, comes to the section of the mineral from below with normal incidence. Since the mineral plate is doubly refracting there are two rays, ordinary and extraordinary, for each one of the components of the white light. These two rays *O* and *E* are each plane polarized and they vibrate at right

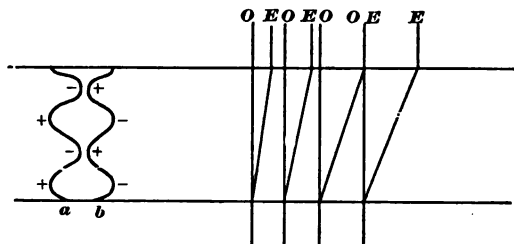


FIG. 6.

angles to each other. Consider any component of white light, as for instance red light. For red light the extraordinary ray, as being refracted, has a longer path to trace than the ordinary ray for red. The extraordinary ray may emerge from the mineral plate a whole wave length,  $\lambda$ , a multiple of  $\lambda$ , or a fraction of  $\lambda$  behind the ordinary ray. In the case where *E* emerges a whole  $\lambda$  behind *O* the two rays vibrate at right angles to each other until they reach the upper nicol. In it they yield opposite and equal components with the result that the red ray is not able to get through the upper nicol and is lost. The resultant light will be white light minus the red component. Again if the ray *E* emerges just  $\frac{1}{2}\lambda$  behind *O* for red they will yield such components in the upper nicol as to permit the red light to pass through it most strongly.

Only those rays which have the same wave length can interfere. Thus  $a$  and  $b$  (Fig. 6) in exactly opposite phase and with their vibration directions in the same plane nullify each other. For each of the color components of white light  $E$  may emerge behind  $O$ , and if the retardation amounts to one or more whole  $\lambda$ 's that color is lost by the action of the upper nicol. If the retardation is just  $\frac{1}{2} \lambda$  or a multiple of  $\frac{1}{2} \lambda$  the color gets through the upper nicol. In the end it happens that the color components whose difference between  $O$  and  $E$  is whole  $\lambda$ 's or nearly whole  $\lambda$ 's are lost, and the colors which get through are those which have  $O$  and  $E$   $\frac{1}{2} \lambda$ , a multiple of  $\frac{1}{2} \lambda$  or nearly such an amount apart. These surviving components are mixed together so that a definite color results. The maximum intensity of the colored light appears when the planes of vibration in the section are at  $45^\circ$  to the vibration directions of the nicols for then most light can get through the upper nicol. The light which results from this complex state of affairs is some fraction of the original white light coming from the sun. By far the larger part of the determinations with the microscope is made with crossed nicol light and the resultant colors are very characteristic. They vary for sections of different thicknesses, and for sections cut from a given crystal in different crystallographic directions.

**Determinative Value of Interference Colors.**—If the section is cut parallel to the  $c$  axis, in tetragonal or hexagonal crystals, and therefore parallel to the direction of the optic axis, it will exhibit the maximum interference effect of double refraction, or birefringence, for all sections of the mineral in question. This color will be highly characteristic of the mineral and an observation of it is of great determinative value. For ready comparison with the maximum crossed nicol colors of other minerals such a colored chart as is given at the end of the book (Plate I) is a necessity. In the first place in using it one needs to find in the slide a prismatic section of some common mineral such as quartz. Such a section parallel to the  $c$  axis will give the maximum effect of birefringence for quartz.

The interference color for the prismatic section of quartz is somewhere on the slanting line .009 on the chart. (Plate I.) The intersection of this line with the interference color on the chart corresponding to that exhibited by the mineral is at the point where the horizontal line, giving the approximate thickness of the section in hundredths of a millimeter, lies. That is the chart gives the crossed nicol colors for prismatic sections of quartz corresponding to slides of various thicknesses up to .06 mm. When once the thickness of the section is known in this way the highest interference colors possible for all the other minerals present in the section may be found on the horizontal line, corresponding to the thickness of the section, where this horizontal line crosses the slanting birefringence lines given for these other minerals. (See color chart, Plate I.)

It is to be noted that apatite with a birefringence value, the difference between  $\epsilon$  and  $\omega$ , equal to .004, and nephelite (.005), whose birefringence is very low, can never give brilliant interference colors in rock slides, but only grays and blues. Quartz (.009) reaches yellow in .03 mm. sections. The feldspars from albite to anorthite may be so cut as to show higher colors than quartz, and they often reach yellow. Augite (.025) gives brilliant interference colors notably higher than those for hornblende (.016). The pyroxenes diopside (.029) and ægirite-augite (.029) are marked by brilliant interference colors as are also olivine (.035) and epidote (.038). Minerals with very high birefringence values as ægirite (.050), zircon (.062), titanite (.145), and calcite (.172), show colors of such high orders in which the rays blend to make light approaching white light, that for them the change between ordinary light and crossed nicol light is never marked. A critical study of these effects is of great service in the identification of the several minerals.

#### **Determination of Faster and Slower Rays in Mineral Sections.**

—The colored chart is furthermore exceedingly useful since by its aid we can determine which one of the two vibration directions in a given plate between crossed nicols is the vibration

direction of the slower or faster ray. Having noted the crossed nicol color of the mineral in the  $45^\circ$  position of maximum light when necessarily each of its two vibration directions is  $45^\circ$  from the cross-hairs, we place in the slot provided for the purpose above the objective a thin plate of mica. The mica plate has of course its own two vibration directions, and one of these, the vibration direction of the slower ray is marked on it by an arrow.<sup>1</sup> With the nicols crossed (if the vibration direction of the slower ray, running in the  $45^\circ$  direction, happens to lie over the slower ray of the mineral on the stage, then the effect is that of thickening the plate, bringing its interference color higher up on the chart, (to the right). If on the other hand the vibration direction of the slower ray in the mica plate happens to cross the vibration direction of the faster ray in the mineral section under examination the effect is that of lowering the interference color. Some color lower in the scale (to the left hand) results.<sup>2</sup>

When we are working with long lath-shaped sections of crystals and note that the vibration direction of the slower ray is parallel or nearly parallel with the long direction of the crystal we call the sign of elongation or the elongation character +; and when the vibration direction of the faster ray falls with the long direction the elongation character is -. By referring to the table at the end of the book it will be seen that this test is of diagnostic value in the case of many minerals.

Inspection of the interference color chart makes it clear that with a section of given thickness, .03 mm. for instance, the interference color, which for any mineral is highest for one particular section of that mineral, will in general be lower than the interference colors of minerals whose indices of refraction are higher. More accurately stated, the higher interference colors go with the minerals having the higher values for the difference

<sup>1</sup> A means of finding the direction of the slower ray in the mica test plate is noted on page 39.

<sup>2</sup> For testing minerals having very weak birefringence a gypsum plate may be used in the same manner. It is of such a thickness that it yields purplish-red between crossed nicols. It is very sensitive in its color changes. The effect of the mineral on the gypsum plate is observed.

between  $n$  in the case of their fastest ray and  $n$  in the case of their slowest ray,  $\varepsilon - \omega$ , or  $\gamma - \alpha$ .

By using the color chart and the mica plate we may often determine the positive or negative character of a tetragonal or hexagonal mineral, working on sections in which, by their crystal outlines or in any other way, the direction of the crystal axis  $c$  is known. The vibration direction of the extraordinary ray in the section is the direction of the crystal axis  $c$ . The slower ray is the extraordinary ray in positive crystals. When therefore we determine that the vibration direction of the slower ray is parallel to the  $c$  axis, the mineral is positive. The mineral is positive when  $\omega < \varepsilon$ .

When we are measuring the extinction angles of the amphiboles and the pyroxenes we often need to know whether it is the faster or the slower ray whose vibration direction we take. (See page 36.) To this end we use the mica plate in the manner indicated above.

Plates of isometric minerals, however they are cut, are all alike in their behavior between crossed nicols: they remain continuously dark. There is no optic axis and no figure can be obtained from them by the use of convergent light. This circumstance is of the greatest possible value in enabling us to pick out readily such minerals as leucite, sodalite, noselite, haüynite, analcite and garnet.

Tetragonal and hexagonal minerals have a single optic axis. Parallel to this, the direction of the  $c$  axis, both ordinary and extraordinary rays move along the same path. The extraordinary ray is not refracted. Both rays go through a basal section on the stage of the microscope with no phasal difference and darkness results with crossed nicols. Basal sections of uniaxial minerals yield the uniaxial figure with convergent light. In this respect they are different from sections of isometric minerals. All other sections whether prismatic, or lying between the basal and prismatic sections, are light and dark four times with crossed nicols. The prismatic section yields the maxi-

mum effect of interference with crossed nicols, and gives, consequently, the highest birefringence color possible for the mineral.

**Uniaxial Figure. Determination of Positive or Negative Optical Character.**—The optical character is very readily determined when a convergent light figure is obtained from a basal section.<sup>1</sup> The figure is a dark cross without rings or with one or more rings of colored light (Fig. 7). The cross is dark because over its area all the light is cut out by the nicols. The rings are due to the interference effects out from the center where the rays meet with phasal differences of  $\lambda$ ,  $2\lambda$ ,  $3\lambda$ , etc. Let the quadrants of the figure be designated  $\frac{A}{C} \bigg| \frac{D}{B}$ . The extraordinary

rays in the figure vibrate in directions like the spokes of a wheel, the ordinary rays vibrate at right angles to the radial vibration directions of the extraordinary rays. In positive crystals the extraordinary ray is the slower ray. When therefore a mica plate is put in above the figure so that the direction of its slower ray cuts across the quadrants  $AB$  the direction of its faster ray cuts across the quadrants  $CD$ . The mica plate is of such a thickness that the phasal difference between its extraordinary and ordinary rays, after they have passed through it, just equals  $\frac{1}{4}\lambda$ . This introduces systematic discrepancies in the uniaxial figure. The cross disappears because there is now some phasal difference over its former area. The rings in the quadrants  $A$  and  $B$  appear farther in than they were before the introduction of the mica plate. Slow ray lies over slow ray in their case, the effect is that of thickening the plate, and the conditions for bringing about phasal differences equal to  $\lambda$ ,  $2\lambda$ ,  $3\lambda$ , etc., are met farther in. The dark spot at the center is replaced by a phasal



FIG. 7.—Figure obtained with convergent light from a basal section of a tetragonal or hexagonal crystal.

<sup>1</sup> To obtain an optical figure we first focus with the high power objective and center the microscope. We then introduce a convergent light lens below the stage, cross the nicols, and remove the eye-piece.



difference of  $\frac{1}{2}\lambda$  and at that point there is light. In the quadrants *CD* the conditions are the other way round. The fast ray lies over the slow ray *E*, the effect is that of thinning the plate, and the conditions for bringing about phasal differences equal to  $\lambda$ ,  $2\lambda$ ,  $3\lambda$ , etc., are met farther out than they were before the mica plate was introduced. The rings therefore move out. The dark spot at the center for the quadrants *CD* is broken into two spots. This is the most significant change of all. When the line between these two spots crosses the arrow on the mica plate the mineral is positive. When these two spots are in line with the arrow the crystal is negative.

When a section inclined by some slight angle away from the basal section is used the figure does not lie wholly within the field. The center of the cross goes around outside the periphery of the field in the same direction as the stage is turned. The arms of the cross maintain their true directions N.S. and E.W. Enough of the figure may appear for the determination of the + or - character.

The number of rings occurring in the uniaxial figure (other things being equal, *i.e.*, with the same lens, and sections of the same thickness) depends upon the birefringence values of various minerals. Calcite, with  $\epsilon-\omega$  very high, will have a very sharp cross and several rings. Quartz will have a cross less sharp but still well defined, and only one colored ring is likely to show in the field. Nephelite, with a very low value for  $\epsilon-\omega$ , will have a very poorly defined cross, and no ring will appear in the field.

The study of the optical properties of biaxial minerals<sup>1</sup> may be begun by a careful examination of Figs. 13 and 14, which are drawn to indicate the optical orientation of orthoclase. Fig. 8 should be consulted in connection with them. Rays of light moving out from the center of a biaxial crystal behave for the most part as extraordinary rays, although some rays behave as ordinary rays. Light originating at a central point within the

<sup>1</sup> Orthorhombic, monoclinic and triclinic minerals.

crystal moves out in all directions so that at the end of a given time the wave front for all the rays will be an ellipsoid constructed on three unequal axes,  $X$ ,  $Y$  and  $Z$ , at right angles to each other. Fig. 8 shows the three plane sections  $XZ$ ,  $XY$  and

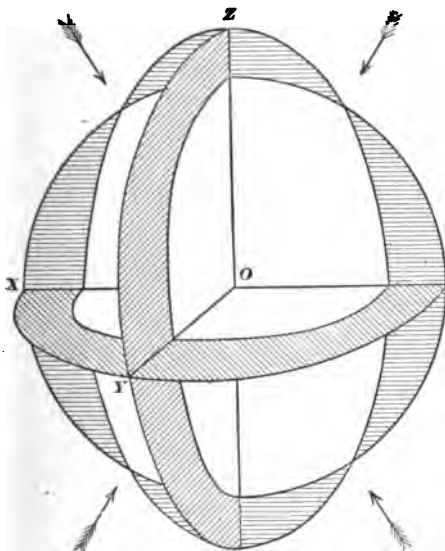


FIG. 8.—Redrawn from Rosenbusch, "Massige Gesteine," I., page 91, 1904. Movement of light in orthorhombic, monoclinic and triclinic (biaxial) crystals. The figure contains three planes of symmetry, at right angles to each other. In each plane of symmetry the wave front for the ordinary rays is a circle, and the wave front for the extraordinary rays is an ellipse. The plane  $XZ$  lies in the plane of the paper. The vertical plane  $ZY$  and the horizontal plane  $XY$  are each at right angles to the plane of the paper. In  $XZ$  the circle intersects the ellipse in four points which are almost exactly the points of emergence of the two optic axes. In  $ZY$  the circle is outside the ellipse. In  $XY$  the circle is inside the ellipse.

$YZ$ , which are planes of symmetry for this triaxial ellipsoid. There are four conical depressions on its surface, opposite to the arrows, Fig. 8. It is not an ellipsoid of rotation for its axes  $X$ ,  $Y$  and  $Z$  are unequal each to each.  $X$  is made proportional to  $\alpha$ ,  $Y$  to  $\beta$  and  $Z$  to  $\gamma$ ,  $\alpha$  being the minimum,  $\gamma$  the maximum, and  $\beta$  an intermediate value for  $n$  in the crystal.

When a random section is cut from a biaxial mineral and placed on the stage of the microscope the normally incident light coming from below will in the great majority of cases be broken into two rays which will behave as extraordinary rays, vibrating in the section at right angles to each other. These two vibration directions in the mineral plate under examination will always correspond, however the section has been cut, to two among the three directions  $X$ ,  $Y$  and  $Z$ .

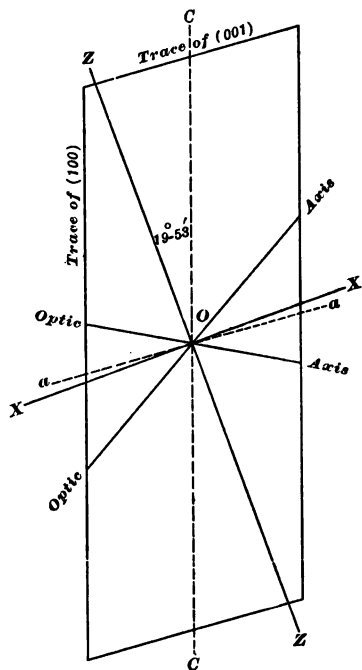


FIG. 9.—Hornblende, (010) section, drawn to show the relative positions of the crystal axes, the optic axes, and the two axes  $X$ , and  $Z$ , of the triaxial ellipsoid shown in Fig. 8.

Fig. 9 is drawn to show the relations between  $X$  and  $Z$  and the crystal axes  $c$  and  $a$  in the plane of symmetry, (010), the clinopinacoid, in hornblende. In this mineral the crystal axes  $c$  and  $a$  meet at angles which are nearly  $74^\circ$  and  $106^\circ$ . The angles between  $c$  and  $a$  are designated as the acute and the obtuse angles between  $c$  and  $a$ .

The concrete statement regarding the movement of light in hornblende is as follows. There are in the mineral three directions at right angles to each other which have, severally, a minimum, a maximum and an intermediate value for  $n^1$ , and light moves through hornblende with different velocities in different directions. In Fig. 8 let a distance measured from  $O$  on  $X$  be made proportional to  $\alpha$ , 1.629, the minimum value for  $n$  in the mineral. Let a distance measured from  $O$  on  $Z$  be made proportional to  $\gamma$ ,

<sup>1</sup> One of many intermediate values.

1.653, the maximum value for  $n$  in the mineral.  $OY$  should be proportional to  $\beta$ , 1.642, the intermediate value of  $n$ . Light starting from a point at the center of the crystal will in a given time move out a certain distance. In the plane of  $X$  and  $Z$ , the plane of the paper, Fig. 8, one set of rays, vibrating parallel to  $Y$ , will advance in all directions with a velocity  $= \frac{1}{\beta}$ , that is  $\frac{1}{1.642}$ . The wave front will be a circle. At the same time, in the same plane, that of  $X$  and  $Z$ , another set of rays will advance in all directions in such a manner that its wave front will be an ellipse. A ray will move in the direction  $OX$ , vibrating parallel to  $Z$ , with a velocity equal to  $\frac{1}{\gamma}$ , that is,  $\frac{1}{1.653}$ . Another ray will advance in the direction  $OZ$ , vibrating parallel to  $X$ , with a greater velocity than the first. Its velocity will be equal to  $\frac{1}{\alpha}$ , that is,  $\frac{1}{1.629}$ ; and in every intermediate direction between  $OX$  and  $OZ$  rays will advance with velocities intermediate between the velocities of the rays on  $OX$  and  $OZ$ . The elliptical wave front of the second set of rays and the circular wave front of the first set of rays, mentioned above, will intersect each other at four points as in Fig. 8. These are the points of emergence of the lines marking the directions of the optic axes.

Similarly, in the plane  $XY$ , one set of rays will have a circular wave front lying entirely inside of an elliptical wave front for a second set; and in the plane  $YZ$  one set of rays will have a circular wave front lying entirely outside of an elliptical wave front for a second set. (See Fig. 8.) Along the directions of the two optic axes light moves with equal velocities, and behaves in such a manner as to recall the single optic axis to which the behavior of light in the uniaxial (tetragonal and hexagonal), crystals is related.

The angle between the optic axes is designated by  $2V$ . In hornblende the value of  $2V$  is about  $60^\circ$ . (See Fig. 9.) In this

mineral  $X$  is the line bisecting the acute angle between the optic axes, and  $Z$  bisects the obtuse angle between them.  $X$  is called the acute bisectrix, written  $Bx_a$ , and  $Z$  the obtuse bisectrix, written  $Bx_o$ .  $Y$  is normal to the plane of the optic axes, the plane (010), in which  $X$  and  $Z$  lie. If we have a section of hornblende cut perpendicular to  $Y$  we can measure the true extinction angle. The direction of the cleavage cracks gives us the direction of the crystal axis  $c$ . We make this parallel to the N.S. cross-hair and with the nicols crossed turn until we get darkness by bringing the vibration direction  $Z$  into line with the cross-hair. By using the mica plate in the manner described on page 29 we can make sure that we have turned to  $Z$ , the vibration direction of the slower ray, and not to  $X$ , the vibration direction of the faster ray. When these relations are clearly understood the statement of the extinction angle for hornblende may be recorded very simply:  $c \wedge Z = 19^\circ 53'$ . The extinction angles measured from  $c$  to  $Z$ , or in other cases from  $c$  to  $X$  are quite characteristic for the several varieties of amphibole and pyroxene, and it is by these means that they are determined, as appears on pages 80, 84 and 87. It is evident that the extinction angle on the section (100) of hornblende will be  $0^\circ$ , for in it there will be no angular difference between the directions  $c$  and  $Z$ . We need, therefore, to know how to recognize the section (010). Since  $X$ , with its value for  $n=\alpha$ , and  $Z$ , with its value for  $n=\gamma$ , both lie in (010), this section will show the maximum effect of birefringence dependent upon the value of  $\gamma-\alpha$ . Therefore no other section will exhibit interference colors that are as high as those given by the (010) section, parallel to the plane of the optic axes.

In the great majority of cases sections cut from a crystal do not happen to be parallel to (010) nor are they perpendicular to one of the optic axes. Normally incident light coming to such sections, including, often, the (010) section, from below the stage is broken into two rays, both of which behave as extraordinary rays, since they are both refracted in the section, and both leave it along lines not normal to its upper surface. Sec-

tions which happen to be cut perpendicular to an acute bisectrix are of great importance for they yield the best figures with convergent light. (See page 38.)

Starting with the above particular statement of the optical orientation of a single monoclinic mineral we may proceed to discuss the optical orientation of the monoclinic, orthorhombic and triclinic minerals in general terms. Minerals in the three systems referred to are called biaxial minerals for the reason that they have two optic axes. The behavior of light in tetragonal and hexagonal crystals is related to one optic axis only. Isometric minerals are in a class apart from all the others, which are doubly refracting, for the reason that isometric minerals are singly refracting.

In monoclinic crystals the plane of the optic axes is not always parallel to (010). It may be at right angles to (010). Of the three axes of the ellipsoidal wave surface of light,  $X$ ,  $Y$ , and  $Z$ , one axis will in any case be parallel to the crystal axis  $b$ , and the two other axes of the wave surface will lie in (010).  $X$  and  $Z$  always lie in the plane of the optic axes.  $X$  and  $Z$  are the bisectrices, and either one may in a given mineral be the acute bisectrix.

The three possible orientation schemes for monoclinic minerals are as follows.

(1)  $X$  and  $Z$  lie in (010) and  $Y$  is parallel to  $b$ .  $X$  may be the acute bisectrix (see Fig. 14 for orthoclase in which the four small circles are the points of emergence of the optic axes), or  $Z$  may be the acute bisectrix.

(2)  $Y$  and the acute bisectrix, which may be  $X$  or  $Z$ , lie in (010). (See Fig. 13 for orthoclase.)

(3)  $Y$  and the obtuse bisectrix, which may be  $X$  or  $Z$ , lie in (010).

When  $X$  is the acute bisectrix the mineral is  $-$ . When  $Z$  is the acute bisectrix the mineral is  $+$ .  $X = \alpha$  and  $Z = \gamma$ .

The optical orientation of orthorhombic minerals is much more easily understood than that of monoclinic crystals. In

orthorhombic minerals  $X$ ,  $Y$  and  $Z$  are each parallel to a crystal axis. The statement of the optical orientation must tell us to which crystal axis each of the three axes of the wave surface,  $X$ ,  $Y$  and  $Z$ , is parallel. We get parallel extinctions on sections of orthorhombic minerals.

In triclinic minerals the axes  $X$ ,  $Y$  and  $Z$  are oblique to the crystal axes  $a$ ,  $b$  and  $c$ . The student needs to have the optical orientation before him in order that he may measure the extinction angles intelligently,

and that he may deal adequately with the convergent light figures referred to below.

**Biaxial Figure with Convergent Light.**—A section cut squarely across the optic axes of a biaxial mineral, *i.e.*, perpendicular to the acute bisectrix, yields a figure with convergent light which in one position is like Fig. 10. This is the  $45^\circ$  position, when the hyperbolæ are farthest apart. When the section is turned  $45^\circ$  away from the position of Fig.

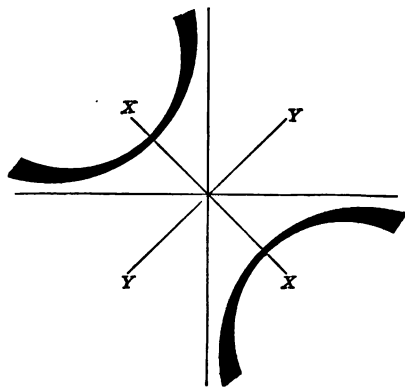


FIG. 10.—Optical figure, in the  $45^\circ$  position, obtained from a section at right angles to the acute bisectrix of a biaxial mineral, in convergent light.

10 the hyperbolæ unite to form

a heavy cross. The middle points of the hyperbolæ, when they are farthest apart, give us the points of emergence of the optic axes. The distance between the hyperbolæ gives us a rough measure of the angle between the optic axes,  $2V$ . The actual angle cannot be measured with the petrographical microscope. When, however,  $2V$  is nearly  $90^\circ$  and we happen to get a section cut at right angles to an optic axis we can recognize the presence of an angle near  $90^\circ$  between the optic axes by the figure. Only one bar shows in the field and as the section is turned the bar does not bend. Olivine illustrates this, see page 75. This is an unusual

occurrence. But when one bar alone shows in the field and this bar bends as the stage is turned we can judge roughly of the size of the angle between the optic axes. The bar will curve sharply when the angle  $2V$  between the optic axes is small; when the angle is large the bar will curve but slightly.

If a thick section of the mica muscovite is used we get an admirable figure. The basal cleavage pieces of muscovite are sections of the mineral almost exactly at right angles to the acute bisectrix. Immediately around the points of emergence of the optic axes are circles of colored light. Longer colored bands surround the whole interference figure. These have the form of lemniscates "figure eight" curves. The colored interference circles and bands are explained in the same manner as the rings about the uniaxial cross. To find the vibration directions at any point in the figure connect the point with the two points of emergence of the optic axes, and bisect the angle thus made at the point in question by the two lines. The bisecting line is one vibration direction and the other vibration direction is at right angles to it.

In mica the direction of the line joining the points of emergence of the optic axes is the vibration direction of the slower ray. The mica test plate referred to on page 29 may be placed upon the stage of the microscope and made to yield a figure. When as in Fig. 10 the hyperbolæ are farthest apart (the  $45^\circ$  position), the direction of vibration of the slower ray may be noted and marked upon the plate with an arrow.

**Determination of the Optical Character of Biaxial Crystals.**—For the determination of the optical character of biaxial minerals a wedge of quartz is used. The quartz is cut in such a way that one side is the prism plane, and the other side of the wedge is inclined slightly away from the prism direction. At the same time it has been so cut that its own vibration directions stand at  $45^\circ$  to its long direction. The introduction of the wedge thin end first is like thickening the plate. The figure is brought to the  $45^\circ$  position. The wedge is pushed in so that



the vibration direction of the slower ray for it is parallel to the line joining the optic axes in the figure. In positive crystals this is the vibration direction of the slower ray. With a positive mineral the circles and lemniscates will contract. If the mineral is negative, and the line joining the optic axes is the vibration direction of the faster ray, the effect is that of thinning the plate and the colored circles and lemniscates will expand for a certain

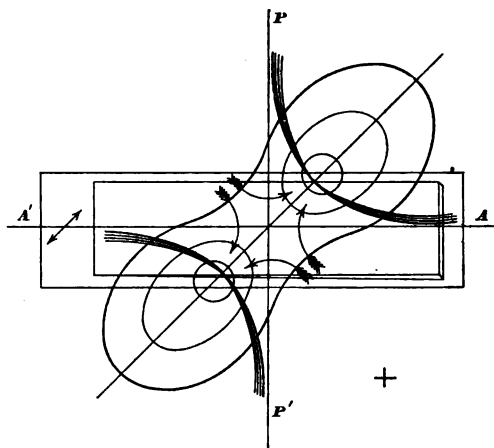


FIG. 11.—Determination of the positive character of a biaxial mineral by the use of the quartz wedge.

time, and then contract. The exact point of this change of motion is marked by the darkened appearance of one of the lemniscates as it is moving away from the optic axes. The quartz wedge should be advanced very slowly, and much care is needed in making the test. Should the quartz wedge be without an arrow to mark the vibration direction of its slower ray it must first be tested with the mica plate (see page 29) and the arrow for the slower ray put upon it. Fig. 11, taken from Phillips' "Mineralogy," page 204, is to be studied in connection with the above discussion.

The plate under investigation may be cut at right angles to one optic axis. Such a section will not change as it is rotated between crossed nicols. Then a single hyperbolic bar appears in the field, bending as the stage is turned. It is important to realize that in all cases where one hyperbola only is seen the convex side of the hyperbola is turned toward the acute bisectrix, *i.e.*, toward that one of the three axes of the triaxial ellipsoid which lies in the acute angle between the optic axes. When a single bar in the field shows that the section is perpendicular to one optic axis it is an easy matter to tell the positive or negative character of the crystal. The section is turned to the  $45^\circ$  position and the mica plate inserted so that the slow ray parallels the plane of the optic axes in the plate to be tested. If the mineral is positive the hyperbola will move toward the acute bisectrix; if the mineral is negative the hyperbola will move away from the acute bisectrix.

**Dispersion of the Optic Axes.**—The angle between the optic axes varies with the color of the light used. This is the phenomenon of dispersion of the optic axes. In favorable cases we may be able to recognize its character. When white light is used the color on the convex sides of the hyperbolæ, (the sides toward the acute bisectrix), tells us the character of the dispersion. It is greater for red light than for blue,  $\rho > \nu$ , when the hyperbolæ are edged with red on the convex sides toward the acute bisectrix, and *vice versa*.

**Possible Determinations with Various Sections of Biaxial Minerals.**—A section of a biaxial crystal which is cut perpendicular to one optic axis may be recognized by its behavior between crossed nicols. If it happens to remain dark during a complete revolution of the stage it is exactly normal to an optic axis. If, however, it is not quite dark during a revolution of the stage, but remains almost dark, without change of illumination, it is cut very nearly perpendicular to an optic axis. Such sections when tested for a figure with convergent light give a single hyperbolic bar. On the other hand those sections

which happen to be cut squarely across the two optic axes, that is, at right angles to a bisectrix line between the optic axes, cannot be recognized as such sections until they are found to give the symmetrical biaxial figure—two hyperbolæ. When both hyperbolæ are present and they do not pass beyond the limits of the field on turning the stage it is safe to say that the section is perpendicular to the acute bisectrix, not to the obtuse bisectrix. We have to do with the acute angle between the optic axes,  $2V$ , given in the tables for the mineral under examination. We cannot, it will be remembered, measure this angle with the petrographical microscope. We can only judge roughly of its size, and if it be so large that the hyperbolæ move out beyond the limits of the field we cannot even tell whether the section is perpendicular to the line bisecting the acute angle between the optic axes, or whether it is perpendicular to the line bisecting the obtuse angle between them. As a matter of fact our knowledge of the positions of the optic axes and of the three axes of the ellipsoidal wave surface  $X$ ,  $Y$ , and  $Z$ , could only have been obtained from sections cut so that their crystallographic orientation was known. The minerals appearing in rock sections have necessarily been cut in a haphazard way. We avail ourselves then of complete records obtained from oriented sections and try in every way possible to judge by crystal outlines or good cleavage cracks how the section has been cut crystallographically. Then assuming that our judgment as to the orientation of the section, whether basal, or prismatic, or parallel to a definite pinacoid, is right, we test it, having in mind the phenomena which such a section of a given mineral should show. In working with a biaxial mineral by testing several of the random sections occurring in the rock we are usually able to get a figure sufficiently good to establish the biaxial character. We may find that some one section proves good enough, on trial, for the determination of the optical character, positive or negative. We may also be able to note the dispersion.

It is most important to remember that in every section there

are two vibration directions which in the position of extinction are in line with the cross-hairs. On a prismatic section (and such sections are often long and lath shaped) we can measure the angle between the direction of the  $c$  axis, known to us by the cleavage cracks parallel to it, and that one of the two vibration directions which runs more nearly parallel with the long direction of the crystal. We read the angle between the cleavage cracks and the extinction position. That gives us a value less than the true extinction angle (which can only be measured on the (010) section). Measuring the extinction angle is then nothing but measuring the angle between the crystallographic axis  $c$  and that one of the three directions  $X$ ,  $Y$ , or  $Z$ , which is nearest to it. In monoclinic crystals it is the clinopinacoidal section which enables us to do this. In triclinic crystals  $X$ ,  $Y$  and  $Z$  have no regular orientation with reference to the crystallographic axis  $c$ . In orthorhombic crystals  $X$ ,  $Y$  and  $Z$  are parallel to the crystallographic axes  $a$ ,  $b$  and  $c$ ; the extinction angle is always  $0^\circ$ , that is we have a parallel extinction.

Sections of biaxial minerals will show the effects of birefringence with crossed nicols. For all biaxial minerals three indices of refraction are given,  $\alpha$  for the direction  $X$ ;  $\beta$  for  $Y$ , and  $\gamma$  for  $Z$ . We refer to such a figure as Fig. 14 for the positions of  $X$ ,  $Y$  and  $Z$ , in the crystal. That crystallographic section of the mineral which is cut perpendicular to  $Y$  will exhibit the maximum effect of birefringence, and it will give the highest crossed nicol color. On the chart this color will correspond to the value given in the tables for  $\gamma - \alpha$ . (See Plate I.)

## CHAPTER IV

### THE IDENTIFICATION OF THE ESSENTIAL MINERALS OF IGNEOUS ROCKS

The successful determination of the minerals in igneous rocks comes in the end to be largely a matter of knowing which few are the most distinctive among a score or more of characteristics marking each mineral. Thus among forty minerals each of which has as many definite properties let us say as the letters of the alphabet, we find in practice that mineral number 1 is more surely recognized by an observation of the characteristics *D*, *M* and *N* than by noting all the others. Minerals 5, 6 and 7 may agree in having the characteristics *C*, *F*, *E* and *R*, but at the same time 5 may be the only one having the property *G*; 6 may be peculiar in showing the characteristic *Q*; and 7 may be unlike the others in exhibiting the quality *K*. The above illustration is introduced to indicate the method of treatment followed in the descriptions of the several minerals in this book. The beginner needs more than anything else to be told what are the really valuable diagnostic properties of each mineral. The discussions which follow aim to do this. They do not treat of the properties which experience has shown to be of lesser importance. The table of minerals shown on page 229 emphasizes in bold type these same most useful characteristics, and it also records in plain type the other properties which are not to be neglected although in the beginning they should not weigh as heavily. Their value becomes increasingly important when the number of minerals dealt with is increased beyond the limits contemplated in this book—an account of the minerals of igneous rocks.

The essential minerals in the igneous rocks, those which are

necessarily considered in the classification of the commoner and rarer rocks, are arranged in Groups I and II below.

# IMPORTANT MINERALS IN IGNEOUS ROCKS

## Group I

Colorless under the microscope in ordinary light.

<b>Alkali Feldspars</b>	{	Orthoclase	}	<b>Plagioclase Feldspars</b>
		Soda-orthoclase		
		Microcline		
		Soda-microcline		
		Microperthite		
<b>Calci-alkalic Feldspars</b>	{	Albite		
		Oligoclase		
		Andesine		
<b>Soda-calcic Feldspars</b>	{	Labradorite		
		Bytownite		
		Anorthite		
<b>Quartz</b>				
<b>Feldspathoids</b>	{	Nephelite		
		Leucite		
<b>Olivine</b>				

## Group II

Colored under the microscope in ordinary light, with the exception of Muscovite and Diopside which are colorless.

Micas	{	Muscovite
		Biotite

<b>Amphiboles</b>	{	Hornblende
		Basaltic Hornblende
		Barkevikite
		Arfvedsonite
		Riebeckite
<b>Pyroxenes</b>	{	Hypersthene
		Diopside
		Augite
		Aegirite-augite
		Aegirite
		Acmite

The separation of the colorless minerals in ordinary light under the microscope from those which are colored is made almost unconsciously, but it is an important first step in their determination. It should be noted that although a mica, an amphibole, and a pyroxene near each other in the same slide may have nearly the same color, green, or brown, or yellowish, as the case may be, still a peculiar tint of the color will be found to characterize each one. The ability to recognize these color tones which are of diagnostic value is gained only by continued use of the microscope.

In the description of the minerals in Group I it is well to begin with the feldspars since the determination of the character of the feldspar in a rock is of critical importance, and feldspar is often the most abundant mineral present in an igneous rock.

### **Weathering of the Feldspars**

All feldspars are apt to show peculiar signs of weathering or decay which do not appear on quartz, a very stable mineral chemically, nor on olivine, nor in the same degree on leucite. Nephelite, however, may exhibit marks of weathering similar to those on feldspar. In many instances crystals of the several feldspars are perfectly clear and glassy. The appearance of weathering

should not be overlooked when it is present. Orthoclase when it decays may be changed to fine scaly aggregates of the mica sericite, or to kaolin and quartz. These products of decay cloud over the surface of the weathered mineral. A similar change may affect all the other feldspars. This "graying over" of their surface may have proceeded so far as to interfere greatly with the passage of light through them. The phenomenon is well seen in all its stages under the microscope.

**Twinning of Feldspars.**—Examination with crossed nicol light may at once suffice for making the distinctions among orthoclase, microcline, and plagioclase feldspar because it brings out the characteristic twinning effects. These will not appear, however, unless the crystals happen to be cut so as to show twinning. Again crystals of untwinned feldspars of all kinds are met. What we must do, then, is to look the slide over for twinned crystals which happen to be cut so as to give us the evidence we need. In favorable cases orthoclase shows simple twinning on the Carlsbad law; microcline has a peculiar twinned appearance all its own, quite unlike that of orthoclase or of the plagioclases; and the plagioclases are characterized by multiple twinning on the albite law.

**Microcline.**—Of the feldspars microcline is perhaps the easiest to recognize. If a crystal of microcline happens to be cut in any direction perpendicular to (010), the appearance of the mineral between crossed nicols is like that shown in Fig. 12. The twinning is in two sets of fine lamellæ, one set on the albite law, the other set at right angles to the first on the pericline law. The cross-bars of the "grating" thin away or wedge out. As the stage is turned completely round the mineral becomes light and dark four times, and the minute bars alternately wax and wane in intensity. If the section be very thin the general interference color is blue-gray. If the section be rather thick yellows and reds appear with crossed nicols. The descriptive term "Rob Roy plaid" has been applied to microcline under such circumstances. Sections of microcline which are



not cut perpendicular to (010) show similar twinning effects but the two sets of lamellæ do not intersect at right angles. They may meet at so sharp an angle as to be sub-parallel, and there is then a slight chance of confusing them with the clear-cut twinning lamellæ of plagioclase feldspar. The twinning lamellæ of microcline may still, however, be safely recognized by their tendency to wax and wane as the stage is turned. Sections of microcline which do not show twinning may be determined by their extinction angle. (See page 60.)



FIG. 12.—Microcline between crossed nicols showing lattice structure twinning. An included crystal of plagioclase with albite twinning appears in the lower right-hand corner.

**Soda-microcline.**—When microcline contains such amounts of soda as to be molecularly in excess of the potash it is called soda-microcline, or anorthoclase. Soda-microcline is recognized by the fact that its twinning pattern is developed with excessively minute lamellæ. The lamellæ may even be sub-microscopic and only recognizable in very thin slides. Sections which happen to be cut at right angles to (001) and at the same time to (010), in other words perpendicular to the crystal axis *a* are peculiarly

valuable. "In these sections highly twinned areas pass into others free from twinning without any visible boundary between them."<sup>1</sup>

**Orthoclase.**—Orthoclase is most easily recognized in crossed nicol light by its twinned appearance in accordance with the Carlsbad law. The twinning axis is  $c$  and the composition face is (010). All sections perpendicular to (010) or nearly so, in other words all sections parallel or nearly parallel to the crystal axis  $b$ , show the twinning in two parts which take the light differently as the stage is turned between crossed nicols. One part may be gray-blue while the other is yellowish, or *vice versa*. The difference between the two is most strikingly shown when the

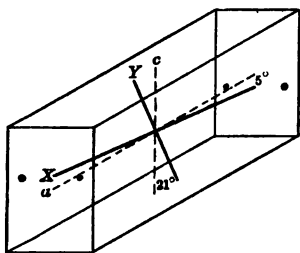


FIG. 13.—Optical orientation of orthoclase.

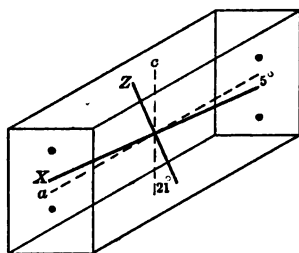


FIG. 14.—Optical orientation of orthoclase.

line between them is at  $45^\circ$  to the cross-hairs. Some orthoclase individuals are not twinned, or it may happen that the section is so cut as to pass through only one of the two parts of the twin. When we cannot see twinning we can prove that the mineral in question is a feldspar by its figure in convergent light, but it may be difficult to determine what particular feldspar we have. Dependence must be placed on the extinction angle. (See page 60.)

**Plagioclase.**—The series of the plagioclase feldspars, which are isomorphous mixtures of the albite,  $ab$ , ( $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$ ) and

<sup>1</sup> Luquer, "Minerals in Rock Sections," page 78.

anorthite, *an*, ( $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ ) molecules, may conveniently be sub-divided as follows:

Albite,	$\text{Ab}_1\text{An}_0$ to $\text{Ab}_6\text{An}_1$
Oligoclase,	$\text{Ab}_6\text{An}_1$ to $\text{Ab}_3\text{An}_1$
Andesine,	$\text{Ab}_3\text{An}_1$ to $\text{Ab}_1\text{An}_1$
Labradorite,	$\text{Ab}_1\text{An}_1$ to $\text{Ab}_1\text{An}_3$
Bytownite,	$\text{Ab}_1\text{An}_3$ to $\text{Ab}_1\text{An}_6$
Anorthite,	$\text{Ab}_1\text{An}_6$ to $\text{Ab}_0\text{An}_1$

The twinning of the plagioclase feldspars is highly characteristic for in their case multiple twins on the albite law are common. The twinning plane is (010) and this is also the composition plane.

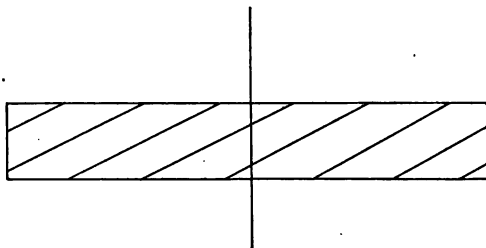


FIG. 15.

All sections perpendicular or nearly perpendicular to this plane will show a number of twinning lamellæ side by side, Fig. 19. It is to be noted that such sections are commonly met, but that some exhibit the twinning bands more sharply outlined than others. This may be caused by the direction the section happened to take across the lamellæ. If the mineral is cut squarely across them we can recognize this fact by noting that sharp clear lines separate the lamellæ. It is important to know this, as will appear later. If, as in Fig. 15, the lamellæ have been cut at an angle, then normally incident light coming to the section from below the stage of the microscope passes across two or more bands on its way through the mineral. In such cases the lamellæ do not appear sharply

defined against each other. There is a wavy extinction with poorly defined dark boundary lines between them. Still the twinning is so characteristic that one knows one is dealing with a plagioclase feldspar. In rare cases one might mistake a crystal of plagioclase which showed the twinning effect poorly in this kind for a crystal of microcline with its albite lamellæ all running in a single direction and sub-parallel. The albite bands in plagioclase are, however, in all cases much more sharply defined than are the lamellæ of microcline. As we examine slides under the microscope we are almost sure to find in them some individual crystals which will give us the evidence we need: the "gridiron" twinning will appear on microcline; orthoclase will be twinned in two parts on the Carlsbad law; and a plagioclase will show multiple twinning on the albite law. (See Figs. 12 and 46.)

The twinning lamellæ may, as stated above, be sharply defined, or bounded by indefinite blackish lines. In some instances the lamellæ are narrow; again they may be broad. Some may run sharply all the way across the crystal; others may wedge out or be discontinuous. The principal bands on the albite law may be crossed by other lamellæ on the pericline law. In the pericline law the twinning axis is the crystal axis  $b$ . The twinning plane, necessarily at right angles to the twinning axis, is therefore not the crystal plane (010). It is, however, nearly parallel to (010). The composition plane is roughly parallel to the base, (001). In andesine it is parallel to (001). In the basic plagioclases it is inclined (downward and forward), more steeply than the base: in albite and oligoclase it is inclined, (upward and forward), so that it is more nearly horizontal than the base, Fig. 16. The pericline lamellæ taken together with the albite lamellæ of plagioclase may simulate the appearance of microcline, but in the case of plagioclase the twinning is clear cut and sharply defined as compared with the wavy extinctions in the cross-bar pattern of microcline.

A plagioclase crystal may be so cut as not to show the twinning. It is as though the leaves of a book represented albite

lamellæ. A section parallel to the leaves and involving only a single leaf would not show the twinning. In such a case, or in the case of untwinned plagioclase, we cannot tell, or we may make out only by refined work from the extinction angle (see page 58) that the crystal is plagioclase and not orthoclase. We are able to prove readily, however, by an interference figure in convergent light that we are dealing with some feldspar and not with a crystal of quartz, leucite or nephelite.

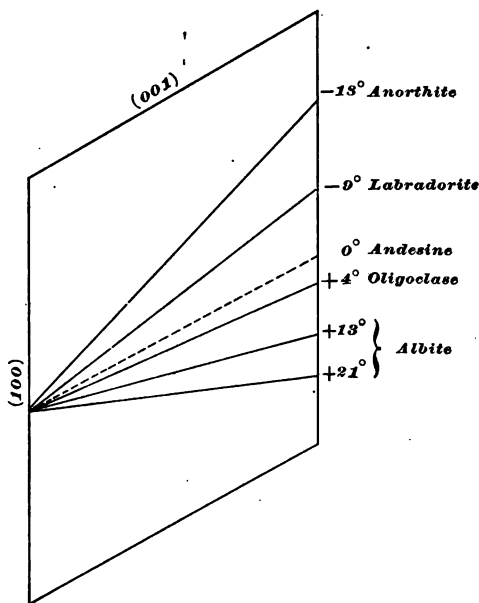


FIG. 16.—Inclination of pericline lamellæ in plagioclase.

**Symmetrical Extinction Angles in Plagioclase.**—It is not enough, however, that the student should be able to recognize plagioclase feldspar as such, for it is of prime importance in the classification of a rock that the particular kind of plagioclase be made out. Albite appears in one group of rocks, those which

contain alkali feldspar. Other rocks are characterized by the presence of andesine or the more calcic lime-soda plagioclases.

The recognition of a particular variety of plagioclase is usually somewhat difficult. Only a fortunately cut section here and there is apt to give us the needed evidence. We must be able to recognize such sections and make the most of them. Very favorable individuals of plagioclase are those which are cut at right angles to (010) and so perpendicular to the lamellæ, and, at the same time are doubly twinned, that is

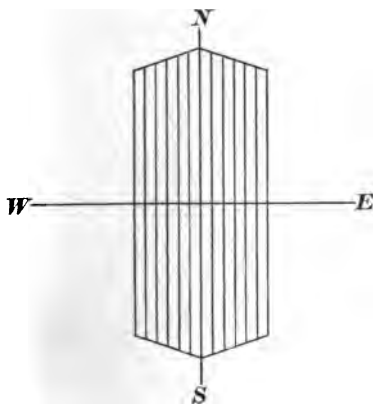


FIG. 17.

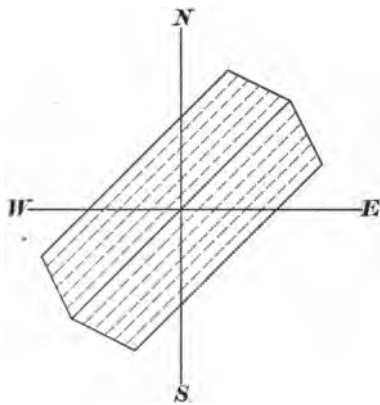


FIG. 18.

twinned on the Carlsbad law and on the albite law as well. Crystals cut squarely across the lamellæ are known by the fact that the boundary lines between the lamellæ are excessively sharp and finely drawn. The doubly twinned condition is recognized with crossed nicols on turning the stage of the microscope more than  $90^\circ$ . When the crystal lies in such a position that the lines between the albite lamellæ are parallel to a cross-hair of the microscope (Fig. 17) the Carlsbad twinning in two parts is not apparent. The albite twinning shows clearly in this position, but the two parts of the Carlsbad twin are almost or

quite alike in appearance. As the stage is turned away from this position the Carlsbad twinning begins to appear, and in the  $45^\circ$  position, half way between the cross-hairs, (Fig. 18), it is seen most clearly since the two parts of the twin take the crossed nicol light with a maximum difference. One part may be gray-blue and the other yellowish. In this position ( $45^\circ$  from the cross-hairs) the albite lamellæ all look alike; they take

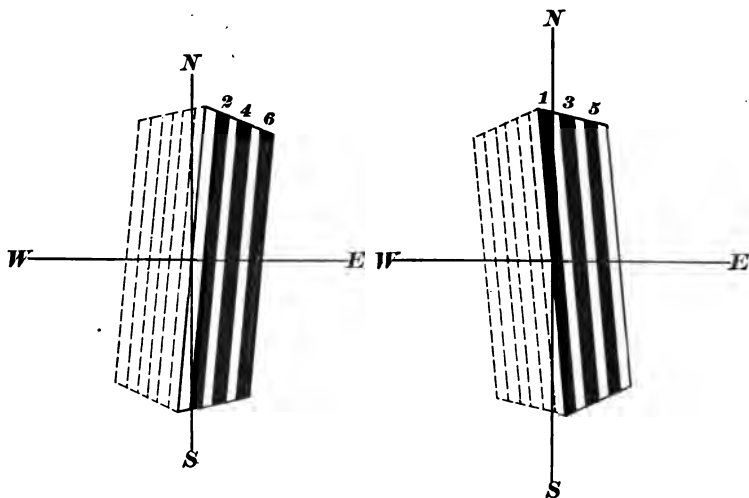


FIG. 19.

FIG. 20.

the crossed nicol light so that scarcely any differences appear among them. The determination of the particular crystal of plagioclase which presents this favorable case rests upon the different values of the extinction angles of the albite lamellæ in the two parts of the Carlsbad twin. In the right hand part of the Carlsbad twin all the even-numbered lamellæ, 2, 4, 6, etc., will become dark for instance at  $5^\circ$  away from the sharp lines between the lamellæ, as in Fig. 19. On turning the crystal on the other side  $5^\circ$  away from the starting point (the position in which the lines between the lamellæ are parallel to the cross-

hair) all the odd-numbered albite lamellæ, 1, 3, 5, etc., become dark, Fig. 20. In this right hand part of the Carlsbad twin the albite lamellæ, (in two sets conveniently called odd and even), show symmetrical extinctions of  $5^\circ$ . The same procedure in the left-hand part of the Carlsbad twin would result in a different value for the symmetrical extinctions of the albite lamellæ, as, for instance,  $30^\circ$ , Figs. 21 and 22. These two values

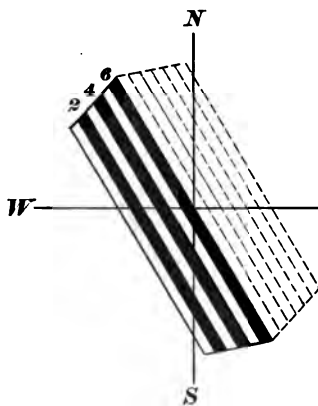


FIG. 21.

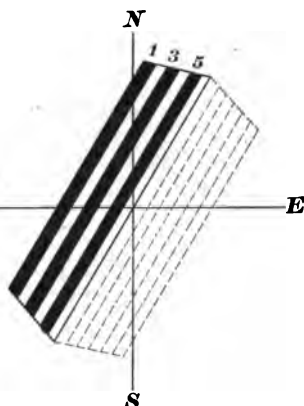


FIG. 22.

for the extinction angles,  $5^\circ$  and  $30^\circ$ , are characteristic of a particular kind of plagioclase, labradorite,  $\text{Ab}_3\text{An}_7$ , and they indicate as well a particular section of the mineral at right angles to (010). Tables have been constructed giving the symmetrical extinctions of the two sets of albite lamellæ in the two parts of Carlsbad twins for every possible section cut at right angles to (010), in other words for all sections in the zone normal to (010). In Figs. 23 and 24 the heavy line gives the symmetrical extinctions of albite lamellæ in one part of the Carlsbad twin, and the dotted line gives the symmetrical extinctions of albite lamellæ in the other part of the Carlsbad twin. By taking the two values obtained in the manner indicated above,  $5^\circ$  and



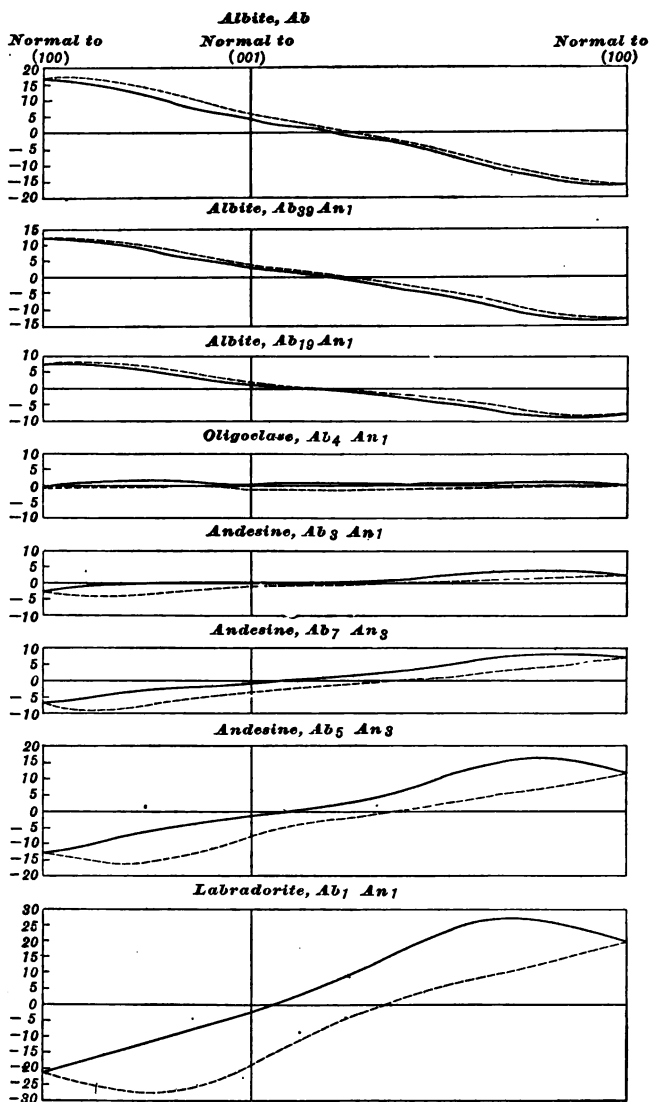


FIG. 23.

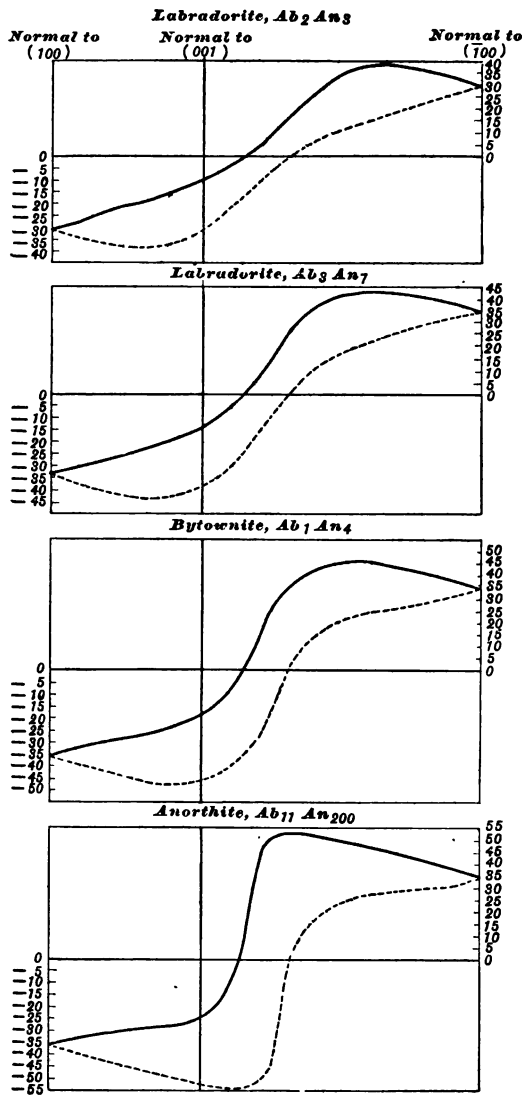


FIG. 24.

FIGS. 23 and 24.—Extinction angles in plagioclase feldspars, which show twinning on the albite law and at the same time on the Carlsbad law, for the two parts of the Carlsbad twins in sections cut normal to (010). Horizontal lines should be drawn at every 5° point in pencil, lightly. Redrawn from Iddings, "Rock Minerals," page 224.

30° and finding two points (one vertically above the other), on the lines for the plagioclase feldspars in the diagram we determine the feldspar in question. In this instance it is labradorite,  $Ab_3An_7$ .

An inspection of the diagrams makes it clear that for albite and oligoclase the two curves depart very little from each other. The symmetrical extinctions in the two parts of the Carlsbad twins are numerically as near together as 5° in these feldspars. In the more calcic plagioclases they are much farther apart. In labradorite they may often be over 20° apart, and in anorthite they are even more widely separated.

**Determination of the Plagioclases and Other Feldspars by the Extinction Angles on Sections Whose Definite Orientation May Be Recognized.**—The methods described below are precise and of the highest value, but the sections needed for making the determinations are of rare occurrence in slides and much care is needed in recognizing them. The useful sections are: 1, those which are parallel to (010); 2, those which are perpendicular to (010) and to (001) at the same time.

1. Sections parallel to (010) are known by the following tests.

(a) The basal cleavage cracks in such sections stand vertically and therefore remain in place without shifting when the focus is raised and lowered. (b) The section will not show twinning on the Carlsbad law nor on the albite law, but pericline lamellæ may appear. These are parallel to the basal cleavage cracks only in the case of andesine. (Cf. page 51, and Fig. 16.) Pericline lamellæ are much rarer than albite lamellæ. (c) The figure in convergent light for the section oriented as in Fig. 16 shows no hyperbolic bar in the case of either albite or oligoclase. In labradorite, bytownite and anorthite, one hyperbola alone appears, in the S.W. quadrant of the field. In labradorite the hyperbola runs N.W. and S.E.; in anorthite the hyperbola runs nearly E. and W., and the point of emergence of an optic axis is visible. In bytownite the position of the hyperbola is intermediate between its positions in labradorite and anorthite. For

orthoclase, soda-orthoclase and microcline the biaxial figure for all positions of the stage is nearly symmetrical to the field. In other words the bisectrix between the optic axes is nearly normal to the plane of the section.

The procedure in measuring the extinction angle on these definitely oriented sections parallel to (010) is as follows. The feldspar is set up with the basal cleavage cracks parallel to the N.S. cross-hair. The trace of the crystal axis  $c$  it is to be noted

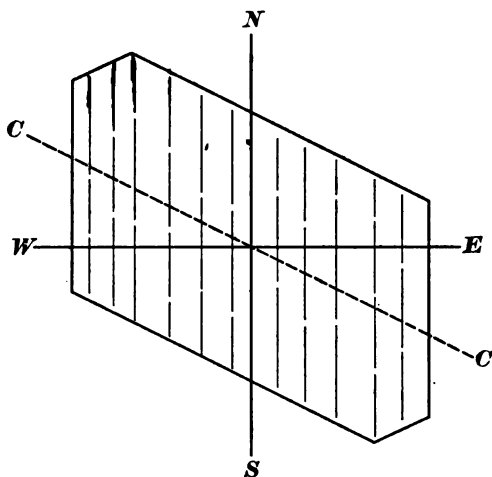


FIG. 25.

makes angles of  $64^\circ$  and  $116^\circ$  (nearly) with the basal cleavage cracks, Fig. 25. The trace of the  $c$  axis may as in Fig. 25 go down from left to right, or as in Fig. 26 it may go up from left to right as the case may be, and both positions may be reached by first using the slide in the usual way with its cover-glass above and then reversing it so that the side holding the cover-glass is down. We turn from the cleavage cracks to the position of extinction. If in so doing we bring the trace of the  $c$  axis at first more nearly parallel to the E.W. cross-hair for either position of the crystal,

Figs. 25 and 26, we count the extinction angle  $+$ . We have turned to a vibration direction which lies in the obtuse angle between the cleavage cracks and the trace of  $c$ . If on the other hand we turn to the extinction position in such a way that the trace of the  $c$  axis at first tends to become more nearly perpendicular to the E. W. cross-hair we count the angle  $-$ . We have turned to a vibration direction which lies in the acute angle between the cleavage

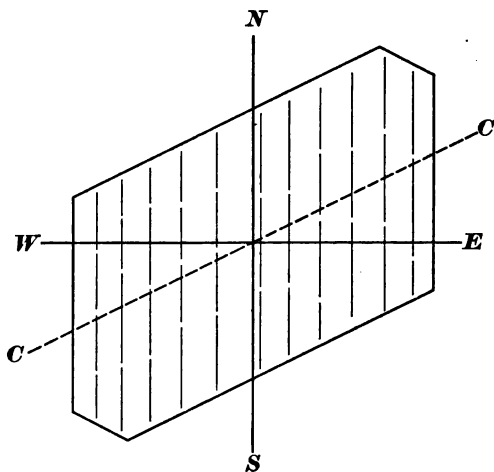


FIG. 26.

cracks and the trace of  $c$ . The statement may be put in another way very briefly. Those vibration directions which lie in the obtuse angle between the basal cleavage cracks and the  $c$  axis ( $116^\circ$ ) are positive, and those in the acute angle ( $64^\circ$ ) are negative. The values for the extinction angles in the lime-soda feldspars obtained in this manner are given in the diagram Fig. 27. The extinction on orthoclase and microcline is  $+5^\circ$  or  $+6^\circ$ . For soda-orthoclase it is higher, between  $+6^\circ$  and  $+10^\circ$ .

**Potassium Barium Feldspars.**—Such readings of the extinction angle on (010) may serve to indicate the presence of the rare

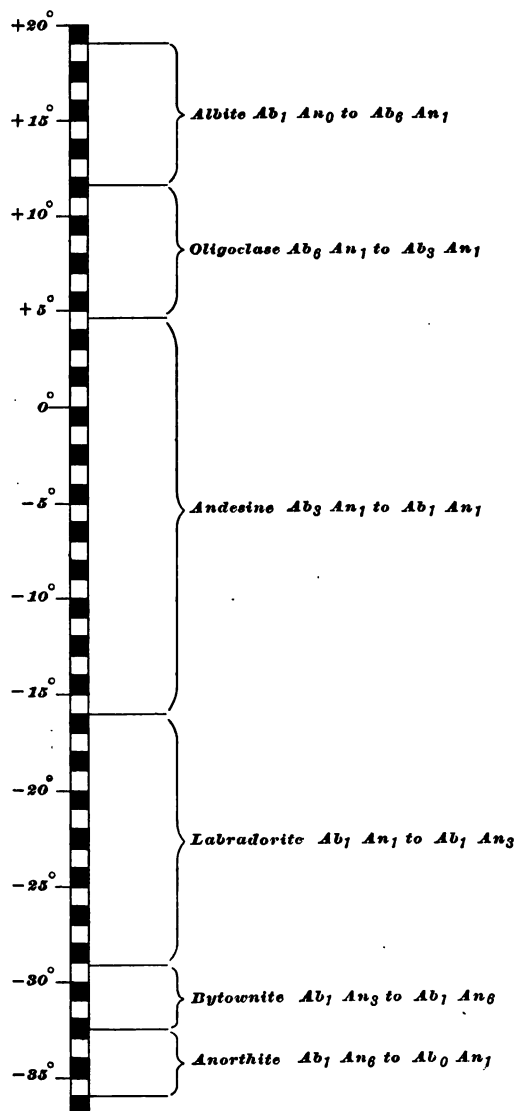


FIG. 27.—Extinction angles on (010) in plagioclase feldspars.

potassium-barium feldspars of the Hyalophane-Celsian series. The molecule of the pure barium feldspar celsian,  $\text{BaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ , (abbreviated, Ce.), is intergrown with the orthoclase molecule, Or, in the hyalophane series. The extinction angles on (010), measured from the basal cleavage cracks to the vibration direction  $X$  in these feldspars are as follows.  $X$  lies in the obtuse angle between  $c$  and  $a$  only in barium-orthoclase.

<b>Barium-orthoclase</b>	{	$\text{Or}_{19}\text{Ce}_1 + 2^\circ$
		$\text{Or}_{10}\text{Ce}_1 + 5^\circ$
		$\text{Or}_4\text{Ce}_1 - 2^\circ \text{ to } -6^\circ$
<b>Hyalophane</b>		$\text{Or}_3\text{Ce}_1 - 11^\circ$
		$\text{Or}_7\text{Ce}_3 - 18^\circ$
<b>Celsian</b>		$-62^\circ$

Hyalophane and celsian since they are not twinned on the albite law, and since they do not show the microcline twinning structure, may only be confused with orthoclase or anorthoclase. In addition to their higher extinction angles on (010) they differ from orthoclase and anorthoclase in the higher range of their indices of refraction. (See Fig. 28.)

\* The success of this method depends entirely upon the sure recognition of the crystal outlines so that the direction of the crystal axis  $c$  can be made out and the sign of the angle read correctly. It is to be borne in mind that while most feldspar crystals are longest on the  $c$  axis, many on the other hand are drawn out on the  $a$  axis. The chance of recognizing the sections parallel to (010) is better than the chance of finding sections parallel to the base on which the outlines are so good that the edges of the prism planes can be used to note the sign  $+$  or  $-$  of an extinction angle read from the cleavage cracks which in basal sections lie parallel to (010). We can take a megascopic crystal of feldspar and cut a section from it parallel to the base so that we know its orientation. Then the sign of the extinction angle read on the base from the (010) cleavage cracks to the extinction position is characteristic for the several kinds of feldspar. (See Fig. 29.)

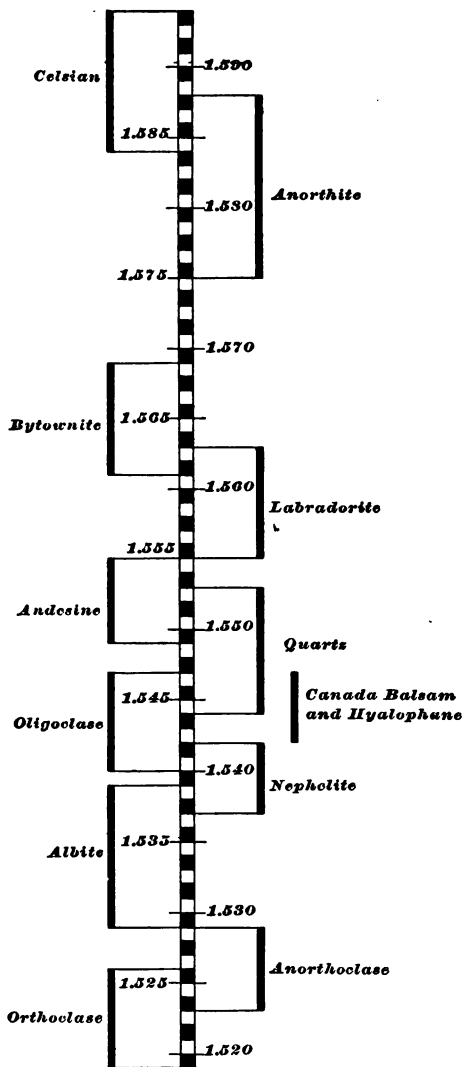


FIG 28 — Values of the indices of refraction in the feldspars, quartz, nephelite and Canada balsam.



But in rock slides where the feldspars are all cut at random it is a matter of extreme difficulty to find a basal section and work

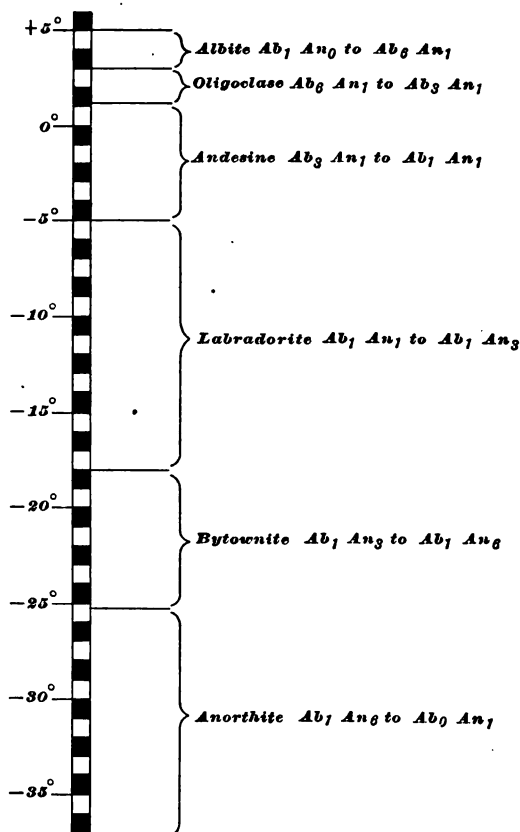


FIG. 29.—Extinction angles on (001) in plagioclase feldspars.

with it successfully. (See Weinschenk, "Petrographic Methods," page 337.)

A particular case of great value in measuring the extinction angle on (010) arises from the fact that the composition face for

the two parts of Carlsbad twins in the lime-soda feldspars may not be in all places parallel to (010). A section may be parallel to (010) and it may still have represented in it the two parts of the Carlsbad twin. The appearance of such sections is shown in Fig. 30. The basal cleavage cracks in the two parts of the twin are opposed to each other and they meet at an angle of about  $128^\circ$ . In this case the direction of the  $c$  axis is the direction of the

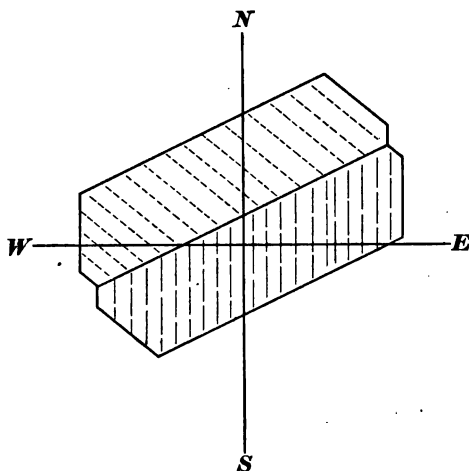


FIG. 30.

line between the two parts of the Carlsbad twin. If as in Fig. 30 we measure the extinction angle in the lower part of the twin and turn to a vibration direction to get darkness in such a way that  $c$  at first comes to be more nearly parallel to the E.W. cross-hair the extinction is  $+$ . We have turned to a vibration direction which lies in the obtuse angle between the basal cleavage cracks and the direction of the  $c$  axis. The sign of the angle is minus when the vibration direction to which we must turn lies in the acute angle between the basal cleavage cracks and the direction of the  $c$  axis.

2. Sections which happen to be cut perpendicular to the two planes (001) and (010) at the same time (normal to the crystal axis  $a$ ), are recognized by the fact that the boundary lines between the lamellæ stand vertically and do not shift when the focus is moved up and down. The cleavage cracks parallel to the base (001) also stand vertically in the section and meet the same test: they do not shift as the focus is changed. Furthermore such sections of the feldspars are nearly rectangular, or square, but

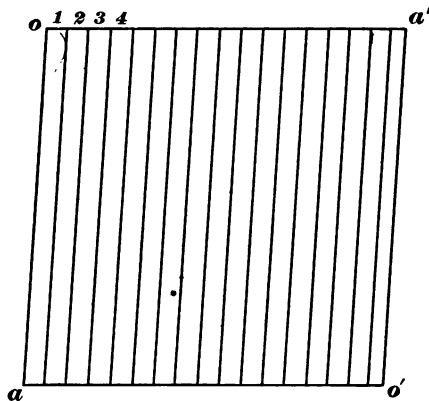


FIG. 31.

not quite so, for as in Fig. 31 the angles  $a$  and  $a'$  are acute, about  $86^\circ$ , while the angles  $o$  and  $o'$  are obtuse, about  $94^\circ$ . This circumstance must be carefully noted. The angle is measured from the direction of the boundary lines between the albite lamellæ to a vibration direction which in one case (+) is more nearly parallel to the diagonal line joining the acute corners of the section and in the other case (-) is more nearly parallel to the diagonal joining the obtuse angles. The success of the method depends upon our being able to observe the acute and obtuse angles in opposite corners of the section. It is to be noted particularly that the two sets of albite lamellæ, odd and even, Fig. 31, will give extinctions of the same angle on either side of the lines between the lamellæ, since the sections in question are cut at right angles to (010). It is necessary, therefore, to work with a single lamella, as, for instance, number 1 of the odd set in Fig. 31 which enables us to note the obtuse and acute angles at the corners and so to read the sign correctly. The orientation of the lamellæ 2, 4, 6, etc., is by the twinning reversed on the lamellæ 1, 3, 5, etc.

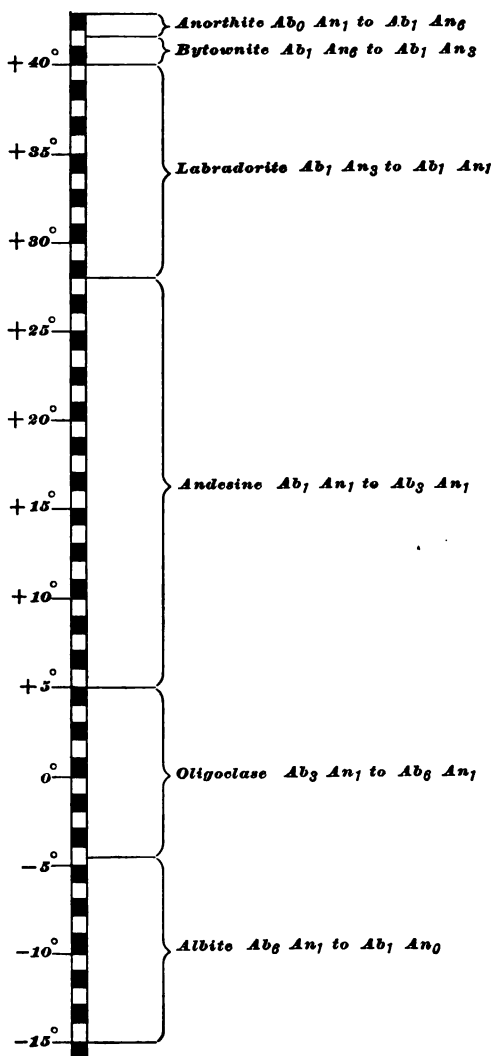


FIG. 32.—Extinction angles in plagioclase feldspars cut at right angles to both (001) and (010).

The values of the extinction angles for the different plagioclase feldspars are given in Fig. 32. An inspection of the diagram shows that many of the values are still characteristic for the particular sections in question even when no attention is paid to the sign of the angle. Values between  $5^\circ$  and  $15^\circ$  may mean either albite or andesine. Other extinctions are definitely bound up with a single feldspar as appears below.

$0^\circ$ to $5^\circ$	Oligoclase
$15^\circ$ to $28^\circ$	Andesine
$28^\circ$ to $40^\circ$	Labradorite
$40^\circ$ to $41\frac{1}{2}^\circ$	Bytownite
$41\frac{1}{2}^\circ$ to $43^\circ$	Anorthite

### Microperthite

Two kinds of feldspar are often grown together with approximately parallel orientation, as, for instance, albite with orthoclase or microcline. Microperthite is the name applied to such feldspar intergrowths. Occasionally the thin bands of albite are crossed by albite twinning lamellæ. More often twinning is not observable and then the Becke test (see page 19) is useful for noting slight differences of refraction between the two minerals.

### Optical Figures in Convergent Light

Should a supposed crystal of glassy feldspar show no twinning effects, either as being untwinned, or if twinned as having been cut so as not to reveal its twinning, there is some danger of mistaking it for quartz or nephelite. The section should be tested for an interference figure. (Cf. pages 31 and 38.) The appearance of two hyperbolæ coming and going in the field, or of a single hyperbolic bar, removes any doubt that the mineral may be quartz or nephelite. On the other hand the uniaxial cross with one ring may serve to establish the occurrence of quartz, and a very poor ill-defined uniaxial figure may mean nephelite.

Leucite will not yield a figure. Olivine has brilliant interference colors and these are never observed in the case of the feldspars.

The beginner can gain control over the methods described above only by considerable practice, but he should work toward that end, for when he can determine the several feldspars he has gone a long way in learning to recognize the minerals most important in rocks with a view to their classification.

### Quartz

Quartz,  $\text{SiO}_2$ , is unlike the feldspars in several respects. In the first place it is chemically stable, and as a result of this its surface does not show effects of alteration. It may be dusted over, or filled with minute inclusions, but the eye soon learns to note the distinction between these conditions and the characteristic appearance of weathered feldspar. Among the important rock-making minerals quartz is the glassy mineral *par excellence*. In the second place quartz, unlike the feldspars, never shows twinning between crossed nicols. Furthermore quartz is never marked by good straight cleavage cracks. It breaks with a conchoidal fracture. We cannot find anything about it for use as a datum line to start from in noting its extinction. This is because there are no good cleavage cracks parallel or perpendicular to the *c* axis, and the outlines of the mineral are almost invariably anhedral, that is rounded or ragged and not the trace of crystal planes. The feldspars on the other hand are very often euhedral, bounded by good crystal outlines. In thin sections the interference colors of quartz are blue-gray. In thicker sections yellows appear, and very thick sections show the bright reds of the first order. Several pieces of quartz side by side in a section, as being cut differently crystallographically, may exhibit a considerable range of colors within the limits possible for the mineral. Cf. Plate I on which the line .009 gives the colors for quartz between crossed nicols. Quartz is often marked by a wavy extinction, that is, between crossed nicols an individual of the min-

eral does not become dark all at once in the position of extinction, but as the stage is turned a dark wave sweeps across it.

The assemblage of characteristics outlined above is in the nature of negative evidence. The eye recognizes quartz most easily by noting the absence of many of the "ear-marks" of other minerals. In determining quartz we depend finally upon its figure with convergent light. To obtain the uniaxial figure of the mineral we make use of the sections which remain very nearly or quite dark during a complete revolution of the stage. By this behavior we recognize the basal section. When the slide is not extremely thin the figure of quartz with convergent light is a clear cut uniaxial cross accompanied by a single ring well out from the center of the field. This ring has red on its outer edge and blue on its inner edge. Sections approximately parallel to the base which do not remain dark between crossed nicols, but show only small changes in the interference tint give serviceable figures. The center of the cross may be outside the field but the quadrant which appears with part of a bar and part of a colored ring is of great determinative value. When a figure of quartz has been obtained it is the work of but a few moments with the mica plate to determine the optical character after the manner indicated on page 32. Quartz is positive.

### **Nephelite**

It is often a difficult matter to recognize nephelite under the microscope. It resembles feldspar and although it is uniaxial while feldspar is biaxial it is by no means easy to obtain a figure in convergent light which is at all satisfactory unless the slide is extremely thick. Nephelite occurs in nephelite-syenite, and in this and allied nephelite-bearing phanocrystalline rocks, since the mineral is anhedral, its presence can best be established by microchemical tests, as will be pointed out later. When, however, nephelite is found in the phonolites it is often easy to recognize it.

In phonolite and other nephelite-bearing lavas although the mineral may be anhedral or subhedral still it is often euhedral, *i.e.*, bounded by good crystal outlines. When nephelite is euhedral its forms are very characteristic. The mineral is hexagonal and its usual crystal habit is that of a simple hexagonal prism short on the *c* axis. Almost all the cuts through these stubby prisms are apt to yield square or rectangular sections. (See Fig. 47.) Such individual crystals of nephelite are as a rule very small, not more than a few hundredths of a millimeter across. They are never twinned. Crystals of untwinned feldspar are occasionally found which resemble them closely. Since nephelite is uniaxial it yields parallel extinctions. We use the sides of the little squares or rectangles in noting the extinction. When the sides of the crystal sections are parallel to the cross-hairs between crossed nicols the mineral is dark. This condition may be met now and again by little square or rectangular crystals of untwinned feldspar which happen to be so cut as to give parallel extinctions. More often, however, such small feldspars will not yield parallel extinctions. The safe procedure, then, is to examine a fairly large number of the little squares between crossed nicols. If they all yield parallel extinctions they are almost surely nephelite. Crystals of the mineral which are cut parallel to the base are six-sided. Such sections are not common and when they occur in phonolite they are apt to be too small to yield a satisfactory uniaxial cross. Nephelite will not be found in a rock containing quartz. If leucite be observed in the rock the presence of nephelite may be suspected. The interference colors of nephelite are bluish-gray, very like the colors of certain sections of the feldspars. In very thin sections no figure can be obtained from nephelite owing to its low double refraction (.005). Even with very thick sections the uniaxial cross is poor, not sharply marked but blurred, and no ring appears out from the center of the cross. Basal sections which remain dark at all times between crossed nicols are needed for this figure. Nephelite is optically negative. Since we cannot



expect to get a good uniaxial figure we determine the negative character of the mineral by the use of the mica or gypsum plate after the manner described on page 30, by finding that it is the faster ray which is parallel to the trace of the optic axis. We are not able to do this unless from the crystal outlines of a given individual we can be sure of the direction of the *c* axis.

In a granitoid phanocrystalline rock the pieces of nephelite will have ragged outlines (appearing anhedral) and we cannot tell the direction of the *c* axis. The easiest way out of the difficulty is to make a microchemical test. Nephelite gelatinizes with HCl whereas such minerals as quartz and the feldspars are not affected by HCl. The slide is prepared by making a scratch with a diamond across the cover-glass. After heating to melt the Canada balsam, when a portion of the cover has been removed and a part of the thin slice of rock laid bare, it is necessary to wash away all the Canada balsam with alcohol and benzole. Dilute HCl is then applied and the section is warmed very gently. After the nephelite has been slightly attacked by the acid all traces of the HCl should be washed away. A few drops of water in which is a very dilute solution of fuchsin may then be applied to stain the surface of the gelatinized nephelite. Finally the section is washed, and the individuals of nephelite stand out in red among the other minerals.

### Leucite

Leucite is recognized by its crystal outline, by its behavior between crossed nicols, and by the absence of such twinning as marks the feldspars. Leucite crystallizes in the form (211), the icositetrahedron, so that all possible sections across it yield rounded outlines which are euhedral, or in the great majority of cases subhedral. In some leucites inclusions are absent, Fig. 49, but in others they appear strikingly as black dots zonally arranged (Fig. 48). Leucite as being isometric is isotropic: sections are continuously dark between crossed nicols. Leucite will

not yield a figure in convergent light. This assemblage of characteristics makes it an easy matter to recognize the mineral. There is some slight chance, however, that the beginner may mistake microcline for leucite. Leucite crystallizes from molten magmas in the isometric system at 500° C. As the rock cools down to ordinary temperatures molecular strains are set up in leucite crystals, and, in consequence, anomalous effects of polysynthetic twinning appear between crossed nicols. The smaller individuals of the mineral are altogether dark. The polysynthetic twinning is prominent only in the larger crystals. The superficial resemblance to microcline may at times be misleading, but the double refraction in leucite is much lower than in microcline, and leucite never becomes light and dark between crossed nicols as the stage is turned, in the clear cut manner characteristic of microcline.

### Olivine

Olivine is known by the characteristic outline of its crystals when they are well developed; by its parallel extinction; by its brilliant interference colors between crossed nicols; and by reason of the fact that it is unstable chemically and on alteration gives rise to serpentine.

Olivine is orthorhombic and it happens that by far the greater number of sections of well-developed crystals of the mineral exhibit some tendency to show an outline which at its best appears like that in Fig. 33, a rectangle with pointed ends. Occasionally only one end of this figure is well developed. We make use of it in noting the parallel extinction. When the longer sides of the mineral (nearly or quite parallel to the line from pointed end to pointed end) are set on a cross-hair the mineral is dark between crossed nicols. We have no other way of placing olivine in line with a cross-hair to note its extinction, for the cleavage cracks are poorly developed in it and we cannot be sure that even the more regular cracks which we observe in sections of this mineral

are parallel to the significant directions, the directions of the crystal axes. Olivine is often euhedral when it occurs in rocks which have a groundmass, but in the granitoid rocks it is anhedral; its outlines are altogether irregular. When this is the case the determination is much harder for the beginner, and special care is needed, as noted below.

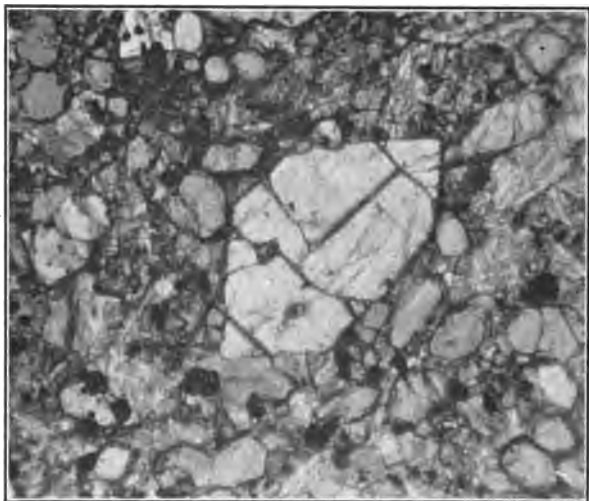


FIG. 33.—Large crystal of olivine well bounded by crystal planes, euhedral, in Olivine-Basalt, Hahn's Peak, Colorado. Ordinary light.

On turning the stage of the microscope olivine crystals often exhibit brilliant interference colors. These are charted for slides of various thicknesses along the line .036 on Plate I. It is to be noted that not every section may happen to be cut rightly to show these brilliant interference colors, for the particular effects of birefringence are directly related to the crystallographic orientation of the section. Again, if the slide is thick, interference colors of such a high order occur that they are not brilliant. Usually a number of crystals of olivine appear in

the field and by examining several of them one or more will be found which show the characteristic brilliant interference colors.

When olivine decays serpentine results. The alteration is best seen along the cleavage cracks in the midst of unweathered glassy portions of the mineral. At times the whole substance of the olivine may be changed to serpentine although the outline of the mass tells plainly the nature of the unaltered mineral.

When in the granitoid rocks we are unable to note the extinction of olivine, as having no crystal outline by which to set the crystal up, we are aided in recognizing the mineral by its brilliant interference colors, and by its marked relief, a consequence of the high value of the index of refraction. Olivine stands out prominently in the section. Its surface has a characteristic rough or shagreened appearance which is more noticeable when part of the light is cut off by diaphragming.

A test of great value is the biaxial figure with convergent light. The angle between the optic axes,  $2V$ , is not far from  $90^\circ$  in olivine. Consequently we are apt to see only one hyperbolic bar in the field, and this bar may remain straight or nearly straight, bending scarcely at all. This is an indication at once of the fact (see page 38) that we happen to have a section cut at right angles to an optic axis, and that the angle  $2V$  is close to  $90^\circ$ .

## GROUP II

### COLORED MINERALS

A first step in the recognition of the remaining common rock minerals, mica, amphibole and pyroxene, is in the observation that with the exception of muscovite and diopside they are colored in ordinary light. It is to be noted that the colors common to one, amphibole for instance, green, yellow and brown, may be found to mark certain individuals among the micas and pyroxenes as well. Each mineral takes particular shades of green, yellow or brown, which to the practiced eye are characteristic, although they can only with great difficulty be adequately de-

scribed. Pleochroism, that is, a change of color as the mineral is turned on the stage in ordinary light, is common to a number of the minerals of Group II, and there is often strong absorption of the light, with consequent darkening in one position with reference to the vibration direction of the lower nicol.

## MICA

The micas occurring in igneous rocks constitute a group of minerals which, chemically, are complex silicates of Al, K and H, with Mg and ferrous iron generally present. Under the microscope one of them, muscovite, is usually colorless. The others are brown or yellow or, rarely, green, as is the case with the common mica biotite.

The most prominent of the physical characteristics of the micas is their extremely good cleavage parallel to the base (001). There is no limit to the fineness of the cleavage plates which may be obtained excepting the delicacy of the instrument used in cleaving the mineral. Certain effects of light in the case of the micas as seen under the microscope hinge upon this eminently good cleavage. By far the larger number of sections will happen to be cut across many cleavage plates and such sections are marked by prominent cleavage lines. Light from below the stage may get through between the cleavage plates more easily than it passes through the mineral itself. Furthermore the single plates as they lie side by side are somewhat crumpled in the grinding of the section so that their surface takes the light differently in different places. The surface of the mica is therefore almost sure to be speckled over with brighter spots. (See Plate II, Fig. 1.) As the stage is turned the effect shows best in certain positions, and disappears in others. At times it is seen to the best advantage with ordinary light: again it appears most strongly with the nicols crossed. For this peculiar appearance which mica does not share with the other colored minerals the term "curly maple" or "bird's-eye maple" has been used. The

resemblance to the wood curly maple is not altogether close but the descriptive term is a good one. The eye soon learns to recognize this peculiarity of the micas and after that it is easy under the microscope to distinguish them from other minerals.

Should the section of mica not show cleavage cracks the effect noted above will scarcely appear. But the sections which do not show cleavage cracks are parallel to the base and such basal sections yield good figures with convergent light. Mica is monoclinic, but when basal sections are euhedral they appear to be hexagonal for they are six sided. The color of basal sections of biotite is often characteristic, a rich chestnut-brown. Various shades are seen according to the thickness of the section. Thick slides may scarcely permit the light to pass through the darker micas in basal sections. When the (001) section of biotite is tested with convergent light the figure consists of two sharply bent hyperbolæ which as the stage is turned scarcely draw apart from each other. The figure is like the uniaxial cross. When thick cleavage pieces of biotite are examined one or more nearly circular rings may appear in the field. In thin slides no rings appear. It will be remembered (page 38) that we cannot measure the angle between the optic axes,  $2V$ , with the petrographical microscope. But when the hyperbolæ do not at any time during a revolution of the stage draw away from each other more than a slight amount we know that the angle  $2V$  is very small. In biotite it is usually not greater than  $1^\circ$  or  $2^\circ$ ; rarely, it is as high as  $40^\circ$ . Muscovite on the other hand is characterized by a large value for  $2V$ ,  $40^\circ$  to  $44^\circ$ . The figure of muscovite (described on page 39) in the thin sections examined under the microscope consists of two hyperbolæ coming and going in the field as the stage is turned. No lemniscates appear for the reason that the section is too thin to show them. The hyperbolæ in the muscovite figure go well apart from each other in accordance with the value for  $2V$ ,  $40^\circ$  to  $44^\circ$ .

The "curly maple" look is seen on muscovite between crossed nicols in sections not parallel to the base which carry cleavage

cracks. For the recognition of muscovite the interference colors in such cases are a very great help. These are a delicate mixture of salmon-pink with dainty greens and blues.

In brief, then, we depend upon the "curly maple" look, upon the figures with convergent light, and upon the colors in ordinary light and with crossed nicols for telling biotite and muscovite. The colors of biotite in ordinary light, brown, yellow, and green, are not peculiar to this mineral, but certain shades of them which the student will learn to recognize for himself are valuable means for telling it. Finally it is to be noted that the extinction in the micas is always parallel or very nearly parallel to the cleavage cracks. Biotite in ordinary light as the stage is turned usually exhibits pleochroism with a change of color from brown to yellow. It also shows strong absorption of the light in certain positions, being strongest (darkest) when the cleavage cracks are parallel to the vibration direction of the lower nicol.

Lepidomelane is biotite rich in iron.

### AMPHIBOLE AND PYROXENE

Amphibole and pyroxene are in many respects so nearly alike that it is well to direct attention at the outset to the points of difference between a representative amphibole, hornblende, and the commonest of the pyroxenes, augite. In cross-section hornblende is six sided; augite is eight sided. The pattern made by the cleavage cracks on basal sections of hornblende is diamond shaped; basal sections of augite show a rectangular cleavage pattern. (Compare Figs. 34 and 35.) Prismatic sections of hornblende yield extinction angles as high as  $20^{\circ}$ . On similar sections of augite extinction angles ranging up to  $45^{\circ}$  are measured. With crossed nicols hornblende as a rule does not show brilliant colors while augite is usually marked by brilliant interference colors. The detailed discussion of the above features in which hornblende and augite are unlike each other is properly followed by an account of their similarities. Finally the important tests

by which the members of the amphibole and pyroxene groups are severally recognized are to be described.

**Crystal Habit of Hornblende and Augite.**—In hornblende the

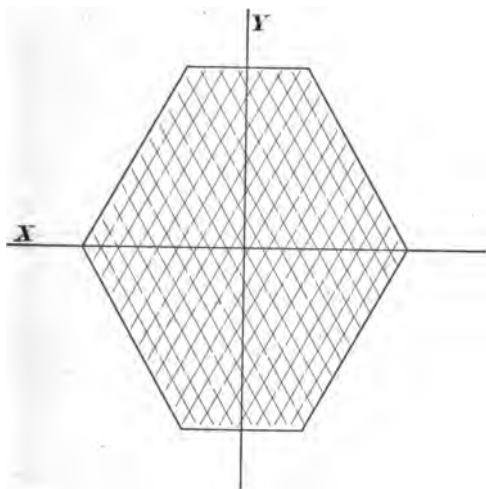


FIG. 34.—Basal section of hornblende with well developed cleavage cracks meeting at an angle of about  $60^\circ$ .

angle between the prism faces (110) is  $124^\circ 11'$ . The six-sided sections of euhedral crystals are completed by the clinopinacoidal faces (010). The cleavage cracks are parallel to the prism faces. They meet at an acute angle of about  $60^\circ$  (Fig. 34.) Augite, like hornblende, is partly bounded by the prism faces (110). These are truncated by the clinopinacoid (010) and by the orthopinacoid (100) as well. Eight-sided cross-sections are the result. The angle between the prism faces is  $92^\circ 50'$  so that the cleavage cracks parallel to the prism meet almost at right angles (Fig. 35.) Observation of the cleavage

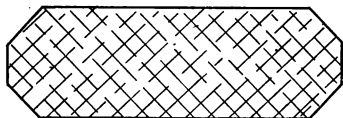


FIG. 35.—Basal section of augite with cleavage cracks meeting at about  $90^\circ$ .



pattern on basal sections is the most satisfactory means of telling hornblende and augite apart.

**Extinction Angles of Hornblende and Augite.**—When a basal section cannot be found we must depend upon the extinction angle, and prismatic sections are selected in order to measure it. These are usually long and narrow, and in them the well marked longitudinal cleavage cracks run parallel to the crystal axis *c* (Fig. 36). All such sections of hornblende or augite have in them two vibration directions at right angles to each other. It will be remembered that when the mineral plate between crossed

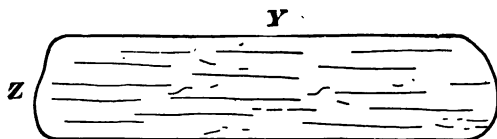


FIG. 36.—Longitudinal section of basaltic hornblende with prominent cleavage cracks parallel to the *c* axis.

nicols has been turned to the position of darkness the two vibration directions in it have been made parallel with the cross-hairs. (See page 25.) The measurement of the angle of extinction is the measurement of the angle between the crystal axis *c* and a vibration direction. The long cleavage cracks in prismatic sections of hornblende are parallel with the crystal axis *c* so that when the cleavage cracks are made parallel with a cross-hair the direction of the crystal axis *c* is necessarily parallel to the cross-hair. The sum of the two angles obtained on turning, with the nicols crossed, from the cleavage cracks first on one side to a vibration direction (position of darkness) and then on the other side to the other vibration direction is  $90^\circ$ . In practice we take the smaller angle of the two for the extinction reading and if we find that we must pass the diagonal position ( $45^\circ$ ) on one side to come to a vibration direction we turn back and go from the cleavage cracks to the nearer vibration direction. For hornblende the extinction angles measured in this way on various pris-

matic sections range from  $0^\circ$  to  $19^\circ 53'$ . For augite angles from  $0^\circ$  to  $45^\circ$  are found. It is clear, therefore, that the measurement of extinction angles on a number of prismatic sections all of which lay below  $20^\circ$  would indicate hornblende and the record of any angle well over  $20^\circ$  would point to the occurrence of augite. In both minerals sections parallel to the orthopinacoid (100) yield parallel extinctions, and the maximum readings are given by sections parallel to the clinopinacoid (010). The (010) sections are the all important ones but the chance of their occurrence in random thin slices of rocks is slight and they are hard to recognize. The precise statement for the extinction angle of hornblende is  $19^\circ 53'$  between the crystal axis  $c$  and the vibration direction  $Z$  in the obtuse angle between the crystal axes  $c$  and  $a$ . (See Fig. 9.) For augite the angle between the crystal axis  $c$  and the vibration direction  $Z$  in the obtuse angle between the crystal axes  $c$  and  $a$  varies from  $38^\circ$  to  $52^\circ$ .  $Z$  is the vibration direction of the slower ray.

**Interference Colors of Hornblende and Augite.**—The numerical range in the birefringence values for hornblende is much the same as for augite. The reason that in ordinary slides hornblende is not marked by brilliant crossed nicol colors while augite commonly exhibits brilliant interference effects is that in hornblende the absorption of the light is much stronger than it is in augite. In rock slides between crossed nicols hornblende is usually dull; some sections of augite have been so cut as not to show brilliant colors, but many pieces will be found which do show them.

**Colors of Hornblende and Augite.**—The colors of hornblende are green, brownish-green, and yellow. Pleochroism, from green to brownish-green, is strong.<sup>1</sup> Augite is often green, brownish-green, and in certain positions yellowish, with much weaker pleochroism than hornblende exhibits. While augite shows many of the colors of hornblende other colors mark it particu-

<sup>1</sup> The method of determining precisely the scheme of pleochroism for hornblende may be understood from the discussion of the pleochroism of basaltic hornblende which appears below.

larly. Augite has a characteristic pale buff color in many basalts, and in diabase augite is often maroon colored or violet-red. These colors are of great diagnostic value and the student should quickly learn to recognize them. (See Plate II, Figs. 2 and 4, and pages 112 and 113.)

**Basaltic Hornblende.**—Basaltic hornblende, barkevikite, arfvedsonite and riebeckite, other important amphiboles, are not of frequent occurrence as compared with hornblende. They are at times difficult to determine. In recognizing them we rely upon their colors, their marked pleochroism, and their extinction angles, measured on (010). For their determination an understanding of the positions of the three axes of the wave surface of light  $X$ ,  $Y$  and  $Z$ , is all important.  $X$ ,  $Y$  and  $Z$  are at right angles to each other.  $X$  is the vibration direction of the fastest ray;  $Y$  is the vibration direction of the intermediate ray; and  $Z$  is the vibration direction of the slowest ray. Their positions are the same in basaltic hornblende and in barkevikite, but the optical orientation of arfvedsonite and riebeckite, as will be seen later, is different. In basaltic hornblende the position of  $Z$ , which lies with  $X$  in the plane of symmetry of the crystal, (010), varies by as much as  $10^\circ$ .  $Z$  may be the direction of the crystal axis  $c$ , or as much as  $10^\circ$  away from  $c$  in the obtuse angle between the crystal axes  $c$  and  $a$ .  $Y$  has the direction of the crystal axis  $b$ , and  $X$  is necessarily at right angles to  $Z$  and to  $Y$ . Bearing these points clearly in mind we select an approximately basal section which we recognize easily by its six-sided outline and by its cleavage cracks. In it (Fig. 34) the two vibration directions are the directions  $X$  and  $Y$  at right angles to each other. By using the mica plate (see page 28) we may note that  $X$  is the direction of the faster ray and  $Y$  that of the slower ray. The vibration direction of the lower nicol is, let us say, as in Fig. 34, in the N.S. position. When the crystal is examined in ordinary light in the setting of Fig. 34 we see its color for light vibrating parallel to  $Y$  and it is brownish-red. On turning the crystal until  $X$  is parallel with the vibration direction of the light from the nicol,

(90° from the original position), we find that the mineral has changed color and is honey-yellow, giving us the color of the light vibrating parallel to  $X$ . To get the color of the light vibrating parallel to  $Z$  we make use of a prismatic section (recognized by the fact that its cleavage cracks run one way only, with the long direction) (Fig. 36) which has a parallel extinction, and is therefore the orthopinacoid (100). The vibration direction of the light from the lower nicol is as before N.S. and the mineral is brownish-red for  $Y$ . We see this when  $Y$ , the vibration direction at right angles to the crystal axis  $c$  is made parallel with the vibration direction of the nicol. We turn the crystal 90° to observe the color when the light vibrates parallel to  $Z$ , *i.e.*, when the direction of the crystal axis  $c$  is parallel to the vibration direction of the nicol. Then the mineral is blackish-brown. We have now the complete scheme for the pleochroism:  $X$ , honey-yellow;  $Y$ , brownish-red; and  $Z$ , blackish-brown. We are in a position to select another prismatic section (010) which has the vibration directions  $X$  and  $Z$  and the corresponding pleochroic colors honey-yellow and blackish-brown in order that we may measure the extinction angle. This section (010), will show the maximum effect of birefringence, and the highest crossed nicol colors of all sections of the mineral. (See page 36.) In such a prismatic section of basaltic hornblende  $Z$  may be from 0° to 10° away from the trace of the crystal axis  $c$ . We set the crystal up in a given case so that the cracks are parallel to the cross-hair and turn 1° 40' with the nicols crossed to the extinction position, that of the vibration direction  $Z$ . We use the mica plate to prove that what we take for  $Z$  is really  $Z$  the slower ray in the section. The above discussion applies directly to basaltic hornblende from Cernosin, described by Tschermak. Other varieties of basaltic hornblende have extinction angles,  $Z \wedge c$ , ranging as high as 10°. Their pleochroism varies from that described for the basaltic hornblende from Cernosin. For a fuller account of the varied pleochroism consult Iddings' "Rock Minerals," 1906, pages 351 and 352.

Basaltic hornblende occurs typically in gabbros and basalts.

**Barkevikite.**—Barkevikite has the same optical orientation as basaltic hornblende. Its determination rests upon its pleochroism which may be worked out in the same way as that of basaltic hornblende, and upon its extinction angles,  $Z \wedge c$ ,  $0^\circ$  to  $12^\circ$  or  $14^\circ$ , in different varieties. The pleochroism is:  $X$ , light brownish-yellow;  $Y$ , reddish-brown;  $Z$ , deep brown. It will be noted that barkevikite is near basaltic hornblende in its pleochroic colors and in the value of the extinction angle.

Barkevikite occurs in magmas rich in soda such as nephelitesyenite.

**Arfvedsonite and Riebeckite.**—Arfvedsonite and riebeckite are soda-rich amphiboles. Their optical orientation, shown in Fig. 37, is different from that of basaltic hornblende and barkevikite. It is the axis  $X$ , that of the faster ray, which lies near the crystal axis  $c$ . The pleochroic schemes for varieties of arfvedsonite and riebeckite are given below.

#### Arfvedsonite

$X$	$Y$	$Z$
Greenish-blue	Blue to gray-blue	Greenish-gray to yellow
Dark bluish-green	Deep blue-green	Light brownish-green
Deep Berlin blue	Light grayish-blue	Light grayish-green
Dark blue	Gray-blue	Light yellowish-green
Dark green	Grayish-violet	Brownish-gray
Dark green	Light yellowish-brown	Greenish-brown

#### Riebeckite

Deep blue	Lighter blue	Green
Indigo, almost black	Blue	Yellowish-green
Deep indigo-blue	Deep blue	Pale brownish-yellow

Extinction angles measured on (010) are as follows:

Arfvedsonite  $c \wedge Z$  (slower ray)  $72^\circ$ ,  $76^\circ$ ,  $80^\circ$ .

$c \wedge X$  (faster ray)  $10^\circ$ ,  $14^\circ$ ,  $18^\circ$ .

Riebeckite  $c \wedge Z$  (slower ray)  $82^\circ$ ,  $88\frac{1}{2}^\circ$ .

$c \wedge X$  (faster ray)  $1\frac{1}{2}^\circ$ ,  $8^\circ$ .

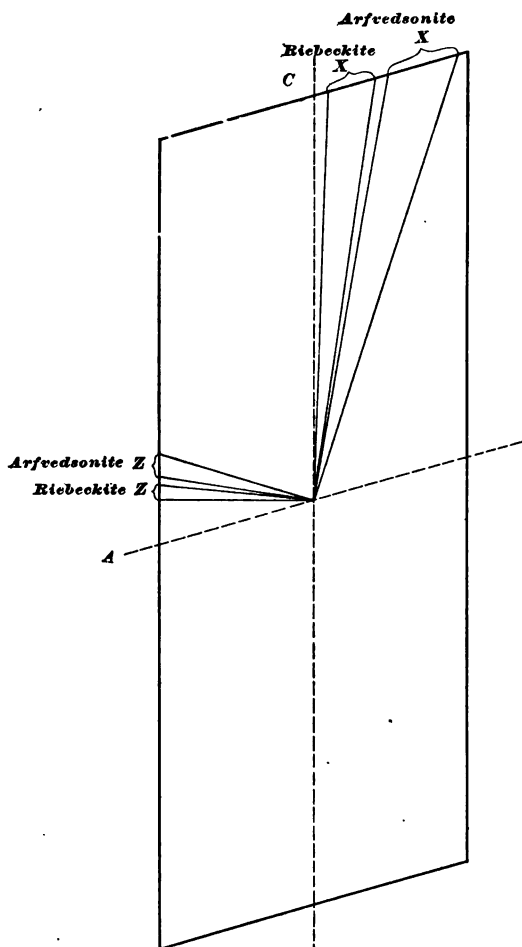


FIG. 37.—Optical orientation of riebeckite and arfvedsonite.

It is always necessary in working with basaltic hornblende, barkevikite, arfvedsonite and riebeckite, to determine the faster and slower rays with the mica plate. The lack of definitely orientated sections and the considerable range in pleochroic colors make the determination of these rarer amphiboles a matter of difficulty.

It helps greatly to know the association. Arfvedsonite, like barkevikite, is met with in soda-rich alkali rocks such as nephelite-syenite. Riebeckite appears in soda-rich alkalic granites and syenites.

### Pyroxenes

Augite is a complex silicate of lime, magnesia, ferrous iron and ferric iron, and alumina, often with small amounts of soda. The composition of the other important monoclinic pyroxenes may be expressed as follows:

Diopside,  $\text{CaO} \cdot (\text{Mg Fe}) \cdot 0.2\text{SiO}_2$ , ideally pure

Acmite,  $\text{Na}_2\text{O} \cdot \text{Fe}_2\text{O}_3 \cdot 4\text{SiO}_2$ , ideally pure

Ægirite-augite, pyroxene with over  $2\frac{1}{2}$  per cent.  $\text{Na}_2\text{O}$ , transitional between augite and ægirite.

Ægirite,  $\text{Na}_2\text{O}$  and  $\text{Fe}_2\text{O}_3$  abundant;  $\text{CaO}$ ,  $\text{MgO}$  and  $\text{Al}_2\text{O}_3$  low.

The rectangular pattern of the cleavage cracks observed on basal sections is of first importance in the recognition of pyroxene, and in its discrimination from amphibole. In the next place the colors are characteristic, especially those which are bound up with the appearance of the soda molecules. Acmite is brown, brownish-green and yellow; ægirite-augite is grass green or sap green; ægirite is clear brilliant grass green. Diopside is colorless.

The appeal to the extinction angles is final. In measuring them sections parallel to the clinopinacoid (010) are needed. Such sections are long and lath-shaped as a rule and in them the cleavage cracks all run one way indicating the direction of the *c* axis. In the (010) sections the maximum effect of birefringence

is given for all possible sections of the pyroxene. This helps in their identification as does also the proof by the symmetry of the figure in convergent light obtained from them that an axis emerges normal to the plane of the section. This axis of the ellipsoidal wave surface of light is  $Y$ .  $X$  and  $Z$  are in the plane (010), inclined at various angles in the different pyroxenes away from the crystal axes. In measuring the extinction angles we deal with the angular distance between the direction of the crystal axis  $c$  known from the direction of the cleavage cracks and the position of one or the other of the vibration directions,  $X$  or  $Z$ , as the case may be. It is always necessary, therefore, to determine the direction of the faster or slower ray in order to know in a given case whether the vibration direction to which the extinction angle is measured is  $X$  or  $Z$ . The extinction angles for the pyroxenes may be tabulated as follows:

<b>Ægirite,</b>	2° to 5° $c \wedge X$ the faster ray
<b>Acmite,</b>	5° to 6° $c \wedge X$ the faster ray
<b>Ægirite-augite,</b>	6° to 38° $c \wedge X$ the faster ray
<b>Diopside,</b>	38° to 45° $c \wedge Z$ the slower ray
<b>Augite,</b>	38° to 52° $c \wedge Z$ the slower ray

**Occurrence.**—Ægirite-augite, ægirite, and acmite appear in nephelite-syenite and in soda-rich varieties of syenite and granite. They are not met with in diorite, gabbro, andesite or basalt. Diopside and augite are of widespread occurrence.

**Diallage.**—Diallage is that variety of augite or of diopside in which in addition to the prismatic cleavages a third cleavage parallel to (100) is well developed. Diallage is common in gabbro and pyroxenite but it is not found in lavas.

**Hypersthene.**—Among the orthorhombic pyroxenes hypersthene,  $(MgFe)O \cdot SiO_2$ , is recognized most easily by its pleochroism. The vibration directions of the wave surface of light are parallel to the crystal axes.  $X$  is parallel to  $a$ ,  $Y$  to  $b$ , and  $Z$  to  $c$ . The scheme of pleochroism is  $X$  red-brown,  $Y$  yellowish-brown,  $Z$  green. There is no easy way of recognizing the orientation of



particular sections as they are encountered in rocks. In practice several sections of the mineral are examined in ordinary light to note whether there is a change of color from green to rose or red-brown. Many other minerals are pleochroic but this particular color change is highly characteristic of hypersthene. The brachypinacoid (010), which exhibits this effect of pleochroism will show the highest interference colors for any section of the mineral since it is parallel to the plane of the optic axes, see page 36. Hypersthene in the thicker sections yields brilliant interference colors of the first order. The extinctions are parallel. Basal sections show prismatic cleavage cracks meeting at a right angle, and with these two sets a third good cleavage parallel to (010) is often developed.

**Enstatite and Bronzite.**—In hypersthene the content of iron is 10 per cent. or over. When Fe is absent or nearly absent the pyroxene is enstatite, a mineral which is colorless or nearly so. The pleochroism in some varieties is yellowish to greenish. Colorless enstatite may resemble diopside but it yields only parallel extinctions.

Bronzite is the variety rich in plate-like bronze-colored inclusions. In it ferrous iron is present to the extent of about 5 per cent.

## CHAPTER V

### DESCRIPTION OF THE ACCESSORY MINERALS OF IGNEOUS ROCKS

**Garnet.**—The garnets are isometric and they form an isomorphous series of orthosilicates. The formulas of five members of the series are given below.

<b>Grossularite,</b>	$3\text{CaO}.\text{Al}_2\text{O}_3.3\text{SiO}_2$
<b>Pyrope,</b>	$3\text{MgO}.\text{Al}_2\text{O}_3.3\text{SiO}_2$
<b>Almandite,</b>	$3\text{FeO}.\text{Al}_2\text{O}_3.3\text{SiO}_2$
<b>Spessartite,</b>	$3\text{MnO}.\text{Al}_2\text{O}_3.3\text{SiO}_2$
<b>Andradite,</b>	$3\text{CaO}.\text{Fe}_2\text{O}_3.3\text{SiO}_2$

Common garnet is made up of the molecules of grossularite, almandite and andradite. The mineral occurs at times in granite. Melanite, dark brown in thin sections, is the variety of andradite which is a common accessory constituent of certain phonolitic rocks. As has been pointed out by Iddings "the garnet occurring in a given igneous rock usually bears some relation to the chemical composition of the rock."

The characteristics by which we recognize garnet under the microscope are its euhedral outlines, sections of the dodecahedron (110) being common; its property of remaining dark at all times between crossed nicols; its high index of refraction; its irregular cleavage cracks, and its colors. Garnet stands out prominently in the midst of the other minerals in the slide. Its characteristic colors are rose-red, brownish-red, brown, yellow, and green.

**Sodalite, Haiynite, Noselite, Analcite.**—These four minerals are to be expected in rocks which contain nephelite or leucite. Under the microscope they exhibit so many properties in com-

mon that the only satisfactory means for their separation is by microchemical tests.

All four are isometric, colorless, and isotropic, that is, dark in every position between crossed nicols. Analcite like leucite takes the form (211), the icositetrahedron. It is, however, very often anhedral. The other three minerals are generally euhedral, the crystal form being that of the dodecahedron (110). Cuts through them yield four- and six-sided cross-sections. For noselite see Fig. 49, large crystal left side. The indices of refraction are low for all four minerals. They look smooth and have only slight relief.

Haüynite is at times blue in thin sections. When it is quite fresh and colorless it will turn blue on heating. Noslite will not do this. Both carry an abundance of minute inclusions. These may be evenly distributed, or they may be centrally arranged, or they may run in lines. Haüynite and noselite usually show a darker border where the inclusions are especially abundant and the substance of the mineral has been weathered. This border does not appear on analcite nor on leucite, and nephelite is not isotropic.

**Microchemical Tests.**—All four minerals gelatinize readily with acid. Sodalite differs from the others in containing chlorine. If its surface be exposed to very dilute  $\text{HNO}_3$  which contains  $\text{AgNO}_3$  in very small amounts the resulting gelatinous silica will be clouded with white  $\text{AgCl}$ .

Haüynite, which contains lime and sulphur, when treated with dilute  $\text{HCl}$  gelatinizes, and, after drying, abundant gypsum crystals are left. Noslite, which does not contain lime but contains sulphur, yields no gypsum crystals or only very few when treated in the same way. If it be treated with dilute  $\text{HCl}$  and a little  $\text{BaCl}_2$  orthorhombic crystals of  $\text{BaSO}_4$  will appear on drying.

Analcite does not respond to any of these tests for it contains no chlorine lime or sulphur. Leucite will not gelatinize readily with acetic acid as analcite will. Furthermore analcite does not

show anomalous twinning effects by any means so frequently as leucite does.

**Melilite.**—Melilite, tetragonal, occurs in tabular form and yields sections which are lath-shaped, with the long direction parallel to the base. The name "peg structure" has been applied to a constant microstructure which is a valuable means of identification. "There start out from the basal terminal plane curious forms shaped like pegs, spears, spatulæ, oars or pipes, which extend to a greater or less depth into the crystal."<sup>1</sup> These inclusions, possibly of glass, are all parallel to the crystal axis *c*, and they lie so that their pointed ends touch the base. The interference color is highly characteristic, indigo or deep purplish-blue. Melilite is found in basic non-feldspathic basaltic rocks, and in certain nephelite and leucite-bearing lavas.

**Zircon.**—Zircon,  $\text{ZrO}_2 \cdot \text{SiO}_2$ , tetragonal, is commonly brownish, or yellowish-brown. It appears in irregular grains and often in euhedral crystals. Sections are square or rectangular and give parallel extinctions. Zircon is characterized by a very high index of refraction, in consequence of which it stands out very prominently from among the other minerals in rock slides. Its double refraction is very high so that brilliant interference colors characterize extremely thin sections. Zircon is usually brown in ordinary light, and it shows no significant change when the nicols are crossed for the reason that its interference colors are too high to be brilliant.

**Tourmaline.**—Tourmaline is recognized by the following well-marked peculiarities. The mineral appears in clear glassy slender hexagonal prisms which have triangular cross-sections, show marked absorption and, often, strong pleochroism. Its index of refraction is fairly high. Its uniaxial figure, a good cross with rings, is obtained from sufficiently large basal sections. Tourmaline is negative. Basal sections have outlines as in Fig. 38. They are usually too small, however, to yield a satisfactory figure, and the determination of the optical character must be

<sup>1</sup> Iddings-Rosenbusch, "Rock-making Minerals," page 161.

made on long slender prisms. These individuals absorb the light most strongly when they are placed across the vibration direction of the lower nicol. In this position we may observe the color when the ordinary ray *O* is used. When the long direction of the

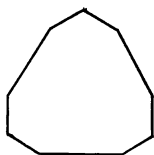


FIG. 38.—Tourmaline. Basal section.

prism runs with the vibration direction of the lower nicol we observe the color of the mineral for the extraordinary ray *E*. Tourmaline may be nearly or quite colorless in thin sections. Much more often bluish-black, blue, brown, green or red appears. The pleochroism in several varieties is as follows:

Brown tourmaline	<i>O</i> dark brown	<i>E</i> light yellow
Green tourmaline	<i>O</i> dark green	<i>E</i> reddish-violet to brownish
Blue tourmaline	<i>O</i> blue	<i>E</i> pale reddish-violet

The extinction is parallel.

**Apatite.**—Apatite,  $3\text{Ca}_3\text{P}_2\text{O}_8 \cdot \text{CaCl}_2$  or  $3\text{Ca}_3\text{P}_2\text{O}_8 \cdot \text{CaF}_2$  hexagonal, is a common accessory constituent of many igneous rocks. It usually appears in minute prisms which share the thickness of the section with other minerals, or as small prisms well bounded by crystal planes. Cross-sections are six sided. The index of refraction is high so that apatite stands out very prominently in the section when compared, for instance, with quartz. At the same time its double refraction is weak and its interference colors (see Plate I) are low, blue-gray, much lower than those of quartz. As being hexagonal apatite has a parallel extinction. The long narrow prisms are often cross-jointed by the development of basal cleavage cracks. If basal sections which are sufficiently large are encountered they will give the uniaxial cross with convergent light, and the negative character of the mineral may be determined with the mica plate.

**Cancrinite.**—Cancrinite is a very rare mineral occurring in soda-rich syenite and in nephelite-syenite, but not in the related lavas, nor with quartz. As a secondary alteration product from

nephelite it is much more common than as a pyrogenetic rock constituent.

Cancrinite is hexagonal. It is colorless in thin sections, yields a good cross with rings in convergent light and is negative. Between crossed nicols its interference colors are brilliant, and at the same time its index of refraction is very low so that it has no relief. Diopside which might be confused with cancrinite has marked relief and stands out from among the surrounding minerals. Diopside is furthermore unlike cancrinite in being biaxial. Orthoclase resembles cancrinite closely but it is biaxial and it will not show brilliant crossed nicol colors. Cancrinite is marked by very good straight cleavage cracks parallel to the prism.

**Corundum.**—Corundum,  $\text{Al}_2\text{O}_3$ , hexagonal, occurs in granite, syenite, nephelite-syenite, in pegmatite, and in some lavas. Its presence plainly indicates an alumina-rich magma. Corundum is a rare mineral.

It is commonly colorless, occurring in prisms or anhedral grains. It yields an indistinct uniaxial cross and is negative. The value of the index of refraction is large and the double refraction near that of quartz. Corundum looks rough. It is distinguished from apatite, quartz and nephelite by its high refraction. Its interference colors are like those of quartz. The cleavage cracks parallel to the base are not observable in thin sections.

**Calcite.**—Calcite is known as an original constituent of the igneous rocks, but the mineral is nearly always secondary and due to alteration. It is colorless, with a high index of refraction, and with very high double refraction. Basal sections remain dark at all times and yield a sharp clear-cut uniaxial cross accompanied by many rings. Calcite is negative. Between crossed nicols the interference colors are of the fourth order so that the mineral is characterized by the admixture of the pale tints which appear at the right hand of the color chart (Plate I). The cleavage cracks parallel to the rhombohedron may be very

prominent. Between crossed nicols they often stand out from the body of the calcite as broad bands of rose or grayish-pink light, the effect being due to the interference phenomena connected with thin films.

**Epidote.**—Epidote, monoclinic, occurs rarely as an accessory pyrogenetic mineral in granite. As a secondary mineral due to alteration it is fairly common. When it is original it is euhedral in very small yellow prisms which stand out prominently in the section. The extinction is parallel to the long direction. As an alteration product epidote appears in clear yellow grains. Between crossed nicols it shows brilliant interference colors in slides of average thickness. Pleochroism may usually be observed.

**Titanite.**—Titanite,  $\text{CaSiTiO}_6$ , monoclinic, occurs in characteristic lozenge-shaped euhedral crystals. The diamond pane like outline of the sections, the very high relief ( $n=1.93$ ); and its rough surface go to mark the mineral. Its colors are commonly dull yellow and brown. There is usually but slight change in the appearance of the mineral after the nicols have been crossed. Titanite then appears darker than it did before, but its color is much the same as in ordinary light.

Among the accessory minerals in rocks a few are metallic and quite opaque. They should be examined by direct incident light after the mirror below the stage has been pushed to one side.

**Magnetite.**—Magnetite,  $\text{Fe}_3\text{O}_4$ , isometric, is the commonest of the opaque minerals. It appears most often in irregular anhedral grains. When it is euhedral some trace of the octahedron (111) is usually apparent. The sections are little squares or rectangles. The surface is bluish-black with high metallic luster. As the stage is turned the light may be reflected from minute smooth mirror-like surfaces.

Magnetite grains are found in almost every rock section. Rhyolite glass is at times filled with a dust of minute magnetite

rods, Fig. 45. The black dot-like inclusions in leucite are partly magnetite, Fig. 48. Calcic plagioclase occurring in gabbro is often permeated by fine magnetite dust, Fig. 40. In basalts and in diabase skeleton growths of magnetite are often prominent.

**Pyrite.**—Pyrite,  $\text{FeS}_2$ , isometric, is opaque. It is known under the microscope by its clear brassy color. The mineral occurs in irregular grains and in small euhedral sections cut from the common crystal forms (100), (111), or (210).

**Pyrrhotite.**—Pyrrhotite,  $\text{Fe}_7\text{S}_8$ , hexagonal, is, like pyrite, opaque. It differs in its bronze color. It is anhedral, occurring in grains.

**Limonite and Hematite.**—Magnetite, pyrite, and pyrrhotite on weathering may give rise to yellow transparent iron rust, limonite, and to clear transparent red stains of hematite.

**Serpentine and Chlorite.**—These two fairly common minerals are due to alteration. Serpentine results from olivine while chlorite is a decomposition product of the pyroxenes. Certain members of the group of the chlorites are indistinguishable by microscopic means from serpentine. Both minerals are apt to occur in formless anhedral aggregates and bunches of fibers. Again they appear as pseudomorphs after the minerals which they have replaced. Serpentine and chlorite are both green, but chlorite is often a much lighter green than serpentine. Again the mesh of fibers in the case of chlorite is usually finer grained than in the case of serpentine. The difference between the two appears most strongly between crossed nicols. The fibers of serpentine have higher double refraction. Yellows appear, to mark some of them, while the remainder are green. On the other hand chlorite between crossed nicols is characterized by lower interference colors in bluish tints. Among these Berlin blue is common.

When it is known that the original mineral which has been replaced was olivine it is safe to say that the alteration product is largely serpentine. Olivine crystals are frequently met in which



the periphery and areas adjoining cleavage cracks have been changed to serpentine; or the whole of the olivine may have been replaced by this mineral without the loss of the original outlines of the crystal.

## CHAPTER VI

### THE IGNEOUS TYPE ROCKS

For a considerable time the beginner should be entirely occupied in familiarizing himself with the main rock types given in the classification table, page 98. He must first gain visual images of the several rocks. Only at a later time need he consider the many sub-varieties, the greater number of which occur very rarely. Many of them have been constituted as such sub-varieties in the course of the most advanced and refined petrographic work. Thus it is better to form a definite image of rhyolite as it looks under the microscope, and then to form an image of trachyte, contrasting the two, than it is to study all the members of the rhyolite family before considering trachyte.

In this chapter brief descriptions of the type rocks are given. Attention is directed to the most important characters which have considerable determinative value, and many details are purposely left out in order that the beginner may get hold of the points of unlikeness among the type rocks.

The granitoid rocks do not present such marked differences in appearance under the microscope as do the lavas. The individual crystals in the granitoid rocks are so large that a few of them occupy the whole field. For this reason, and because the feldspars and nephelite are not to be precisely determined in many cases without careful work, syenite, nephelite-syenite, quartz-diorite and diorite have similar appearances. Granite and gabbro among the granitoid rocks are, however, exceptional in this respect. They show marked individuality.

The first glance at a typical member of the lava series often serves to place the rock very nearly; and its general appearance, in telling us what to look for, guides our effort to determine its

TABLE I.—IGNEOUS ROCKS

ALKALI-FELDSPARS: ORTHOCLASE, MICROCLINE, ALBITE, MICROPERTHITE, SODA-ORTHOCLASE, SODA-MICROCLINE; WITH SUBORDINATE AMOUNTS OF OLIGOCLASE, ANDESINE, AND, RARELY, LABRADORITE.		CALCI-ALKALIC FELDSPARS: CHIEFLY ANDESINE, WITH SOME OLIGOCLASE OR LABRADORITE; ORTHOCLASE OR MICROCLINE MAY BE PRESENT IN VERY SMALL AMOUNTS.		SODA-CALCIC FELDSPARS: LABRADORITE, BYTOWNITE, ANOR- THITE, RARELY A LITTLE ORTHO- CLASE.	
MICA, AMPHIBOLE, PYROXENE		MICA, AMPHIBOLE; Pyroxene subordinate		PYROXENE; Mica and Amphibole subordinate.	
QUARTZ	FELDSPATHOIDS: Nephelite, Leucite	QUARTZ	QUARTZ	OLIVINE	
GRANITE (341, over 10 per cent.) <sup>1</sup> Fig. 1. Plate II.	SYENITE (63, about 3 per cent.)	NEPHELITE-SYENITE (29, over 1 per cent.)	QUARTZ-DIORITE (32, less than 2 per cent.) Fig. 39.	GABBRO (77, about 4 per cent.) Figs. 40, 41, 42.	OLIVINE-GABBRO
			DIORITE (93, less than 5 per cent.)	DIABASE, (in part), (83, about 4 per cent.) Fig. 2, Plate II.	OLIVINE-DIABASE (in part)
RHYOLITE (197, about 10 per cent.) Figs. 43, 44, 45.	TRACHYTE (104, about 5 per cent.) Fig. 46.	PHONOLITE (36, about 2 per cent.) Figs. 47, 48, 49.	DACITE (72, about 3 per cent.)	DIABASE, (in part) BASALT (162, about 8 per cent.)	OLIVINE-DIABASE (in part) OLIVINE-BASALT Fig. 4, Plate II.

Porphyrific Ground-mass Present  
Phanerocrystalline. Granitoid Texture

mineralogy precisely. Thus among the lavas characterized by alkali feldspars there are very real differences between trachyte and phonolite, and between each of these and rhyolite, although it is at the same time true that there are all possible intergradations among members of these three rock families. Very characteristic rock pictures may be set up in the mind which are invaluable as starting points for later studies of the intertype rocks. The type rocks each carry an assemblage of characteristics closely bound up with the chemical composition of their original magmas. Definite groundmasses occur in certain rocks; a mineral common to several rocks is apt to have its own particular look in each one of them; and certain minerals are almost peculiar to certain rocks.

### GRANITE

**Mineralogical Composition.**—Microcline, orthoclase, albite; quartz; biotite, hornblende; small amounts of accessory minerals.

**Texture.**—Granitoid, no groundmass.

**Character.**—Many granites are marked in a striking way by the occurrence of quartz and microcline in abundance. (See Plate II, Fig. 1.) Microcline is more prominent in this rock than in any other. The many individuals of quartz, as having been cut differently in the slide, show the whole range of interference colors possible for a given thickness of the section. They may be dotted over with dust, or they may show tiny cavities filled with gas bubbles. In many granites the quartz is impregnated with exceedingly minute straight hair-like needles which are believed to be rutile. Orthoclase and albite occur frequently in granite. The siliceous nature of the rock is clearly indicated by this assemblage of minerals.

Biotite is the commonest dark silicate, but hornblende may take its place in whole or in part. Muscovite is present in many granites. The accessory minerals are magnetite, apatite, zircon, titanite, garnet and tourmaline.

As soon as quartz is recognized in a granitoid rock the pre-

sumption is strong that it is either granite or quartz-diorite. The occurrence of quartz with microcline or orthoclase indicates granite. Quartz-diorite has andesine as its characteristic feldspar. In this rock biotite and hornblende are apt to be present together, and they generally make up much more of the whole rock than they do in granite.

### SYENITE

**Mineralogical Composition.**—Orthoclase, microperthite, microcline-microperthite, oligoclase; biotite, hornblende, diopside.

**Texture.**—Granitoid, no groundmass.

**Character.**—Syenite differs from granite in being poorer in silica and nearly or quite free from quartz. All possible intergradations exist between granite and syenite on the one hand, and between syenite and diorite on the other. Similarly the syenites and the nephelite-syenites grade into each other. Syenite is a rare rock. Among the accessory minerals present titanite may be especially prominent.

### NEPHELITE-SYENITE

**Mineralogical Composition.**—Orthoclase, microperthite, microcline-microperthite, anorthoclase, albite; nephelite; ægirite-augite, ægirite, diopside; lepidomelane, barkevikite, arfvedsonite, sodalite; melanite and titanite are prominent accessory minerals.

**Texture.**—Granitoid.

**Character.**—This rare rock must be identified by the recognition of nephelite. The presence of this mineral can best be ascertained by a microchemical test, as described on page 72. It is well to remember that nephelite will not be found in a rock containing quartz. It may be suspected in quartz-free granitoid rocks whose constituents point to an alkali-rich magma. The sodic character of the pyroxene will often indicate this condition, *i.e.*, the occurrence of emerald-green pleochroic ægirite-augite or of ægirite. These pyroxenes are highly characteristic of nephelite-syenite, and they are not apt to occur elsewhere in the

granitoid series of rocks. Among the accessory minerals the presence of brown garnet is, similarly, significant. Orthoclase is common, but the absence of microcline with its characteristic grating structure is notable, as is also the absence of the lime-soda feldspars. Albite occurs frequently.

The dark-colored silicates do not as a rule make up more than a small part of the rock, and magnetite and apatite occur very sparingly.

### QUARTZ-DIORITE AND DIORITE

**Mineralogical Composition.**—Andesine and nearly related feld



FIG. 39.—Quartz-diorite. Reichenbach, Hessen. Ordinary light. The dark mineral in the lower right hand corner is biotite, dark brown under the microscope, in the position of maximum absorption. Near the middle of the figure is a small basal section of hornblende with characteristic cleavage cracks. The dark gray pieces are other sections of hornblende, green and brownish-green under the microscope. The colorless mineral surrounded by biotite and hornblende (on the right), is quartz. The other colorless minerals are feldspars.

spar; biotite, hornblende, diallage; as accessories, apatite, zircon and titanite. Quartz characterizes quartz-diorite.

**Texture.**—Granitoid.

**Characteristics.**—Quartz-diorite and diorite form a series distinguished from the granite-syenite series by the more calcic character of the feldspars, which are for the most part andesine and nearly related plagioclases. Biotite and hornblende occur abundantly. Pyroxene is subordinate.

### GABBRO AND OLIVINE-GABBRO

**Mineralogical Composition.**—Labradorite, bytownite, anorthite; augite, diopside, hypersthene; as accessories, magnetite, apatite. Olivine is present in olivine-gabbro.



FIG. 40.—Diabasic Gabbro. Ordinary light. The gray mineral impregnated with magnetite dust is plagioclase, labradorite. The dark mineral which has filled the interspaces between the feldspars is augite. The structure is characteristic of diabase.

**Texture.**—Granitoid.

**Characteristics.**—The distinguishing mark of gabbro is the combination of labradorite or more calcic feldspar with augite or other pyroxene. The rock is so frequently characterized by calcic plagioclase full of dust-like or minute rod-like inclusions of magnetite as often to furnish a ready means of recognizing it.

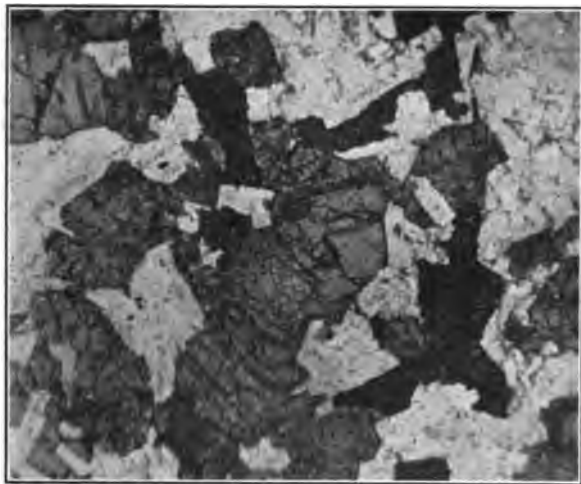


FIG. 41.—Gabbro, St. Peters, South Carolina. Ordinary light. The dark mineral in the center of the figure is augite, with well-developed cleavage cracks parallel to (110). The gray mineral is plagioclase, and the black mineral is magnetite.



FIG. 42.—Crossed nicol light. Same rock as in Fig. 41. The twinning of the plagioclase is apparent, as also the twinning of the augite with (100) as the twinning plane.



(See Fig. 40.) In the feldspars the twinning lamellæ on the albite law are usually broad. Sections which happen to be cut at right angles to the lamellæ (and in such sections the lamellæ are bounded by very sharp lines), may betray their calcic character by their high extinction angles measured from the lines between the lamellæ. The feldspar of gabbro generally shows pericline twinning. Gabbroic rocks occur in which dark colored constituents are almost lacking although some form of pyroxene, either monoclinic or orthorhombic, is a regular constituent of gabbro. When augite has in addition to the cleavages parallel to the prism planes a third well developed cleavage parallel to the orthopinacoid (100) it is called diallage. Diallage is not found in the effusive rocks. This variety of pyroxene is perhaps the commonest in the gabbros. (See Figs. 41 and 42.) When hypersthene is present in notable amount the rock is called norite.

## RHYOLITE

**Mineralogical Composition.**—Orthoclase, oligoclase; quartz; biotite, hornblende.

**Texture.**—A well developed groundmass, often largely glassy, is present.

**Character.**—The distinguishing marks of rhyolite are closely connected with the highly siliceous nature of the magma. Such siliceous acid magmas are far more viscous than the basic magmas. They cool more rapidly and are more frequently chilled. A glassy groundmass is therefore peculiarly characteristic of many rhyolites. The glassy portion of such rocks is recognized by its behavior with crossed nicols. It remains dark at all times while the stage is rotated. (See Figs. 43 and 44.) This glassy groundmass may be iron stained and brown in ordinary light, or it may be colorless and richly impregnated with minute rods and dots of magnetite. (See Fig. 45.)

With somewhat slower conditions of cooling a groundmass may

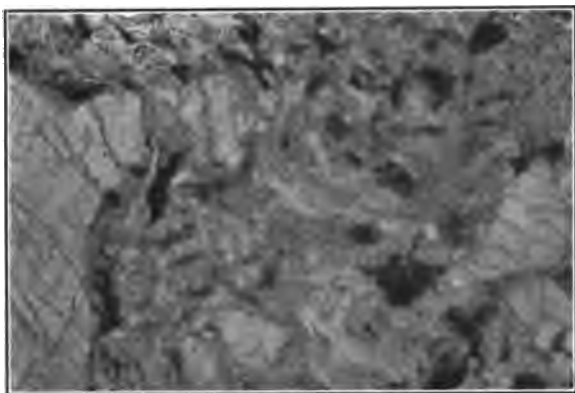


FIG. 43.—Rhyolite. Ordinary light.



FIG. 44.—Same rock as in Fig. 43, but with the nicols crossed. The groundmass remains dark in every position of the stage, since it is entirely glassy. Only a few crystals of orthoclase, untwinned, and of plagioclase, appear in it.

result which is largely a mosaic of little quartz grains and pieces of feldspar. The individual minerals are almost always too small to be readily identified.

With still slower conditions of cooling anhedral rounded pieces of quartz, and euhedral or subhedral feldspars are developed.

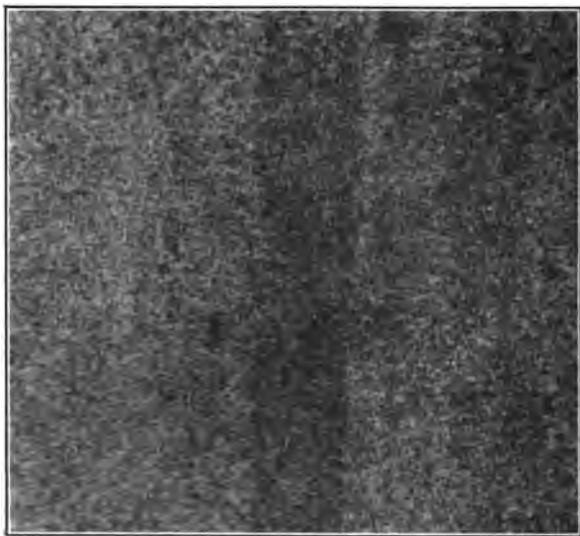


FIG. 45.—Glassy Rhyolite, Tokayer Gebirge. Ordinary light. The felt-like appearance is due to the occurrence of innumerable minute rods of magnetite. The remainder of the rock is a glass.

## TRACHYTE

**Mineralogical Composition.**—Glassy orthoclase; biotite, hornblende, augite, diopside, in small amounts; as accessories, magnetite and titanite.

**Texture.**—The groundmass is usually entirely crystalline.

**Character.**—The peculiar mark of typical trachyte is the development of orthoclase phenocrysts<sup>1</sup> in a groundmass of much

<sup>1</sup> Conspicuously large crystals scattered through a groundmass of smaller crystals, or crystals and glass.

smaller orthoclase crystals (Fig. 46). Glass in the groundmass is unusual. The larger orthoclase crystals which are often clear and glassy are in good Carlsbad twins. The little orthoclase individuals in the groundmass are often too small to show clearly the two parts of the Carlsbad twins which characterize them. When they are viewed under the microscope between crossed



FIG. 46.—Trachyte, Siebengebirge. Crossed nicol light. The occurrence of phenocrysts of orthoclase in a groundmass of small poorly developed orthoclase crystals is characteristic.

nicols one gets at first sight a clear impression that they are distinct from each other; but, on closer examination, they are seen to be packed so nearly together as to indicate that they have interfered with each other's growth. Flow structure is often apparent in the sub-parallel arrangement of these little orthoclase crystals. One can often see how they moved past the larger crystals before the magma became solid. In between the orthoclase crystals of the groundmass are grains of magnetite.

Pyroxene in green anhedral individuals is perhaps the commonest dark silicate. The expression of the whole rock is quite unlike that of rhyolite, phonolite, or the more basic lavas.

## PHONOLITE

**Mineralogical Composition.**—Glassy orthoclase, anorthoclase; nephelite; ægirite-augite, ægirite; noselite, haüynite, sodalite; brown garnet.

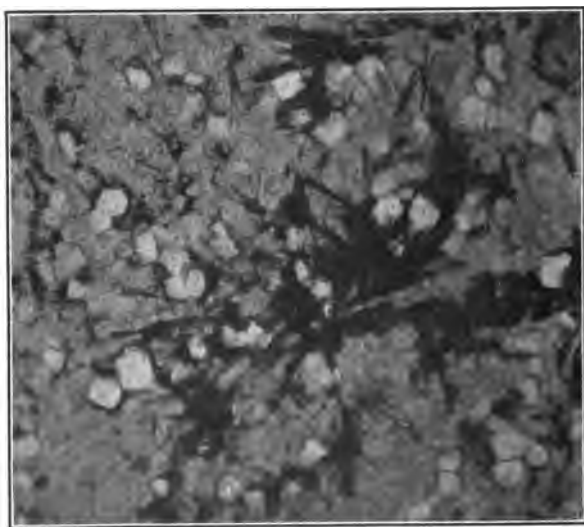


FIG. 47.—Phonolite. Spearfish, South Dakota. Ordinary light. The small rectangular or square crystals are nephelite. The dark mineral which is brilliant grass-green under the microscope is ægirite-augite. Its occurrence in wisps and tufted prisms is characteristic. The remainder of the rock is made up largely of feldspar but this mineral cannot be recognized in the figure.

**Texture.**—Groundmass crystalline.

**Character.**—The series of minerals in phonolite is unique. The occurrence of nephelite serves at once to distinguish the rock

from others in the lava series. Nephelite, owing to its peculiar habit, is very easily recognized. It appears in very small squares, sections of short hexagonal prisms. (See Fig. 47.) Between crossed nicols nephelite takes only the lowest interference colors, gray and bluish-gray. Its extinctions are parallel. Another rare mineral, leucite, in equant<sup>1</sup> crystals having rounded sections,

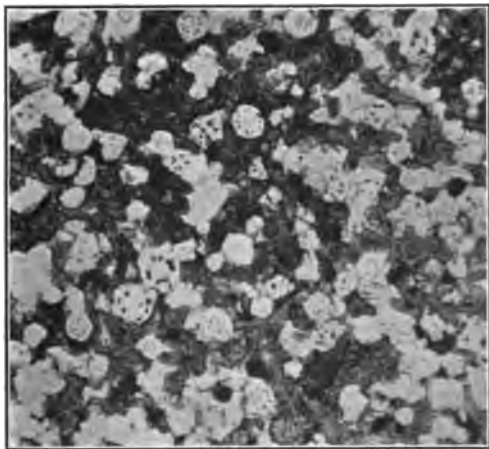


FIG. 48.—Phonolite (Leucite). Capo di Bove, near Rome. Ordinary light. The mineral in colorless rounded pieces is leucite. The black inclusions zonally arranged in it are largely magnetite. The gray mineral in the figure is pyroxene. The large black grains are magnetite.

may be present with the nephelite. Rings of inclusions of black magnetite dots sometimes occur in leucite (Fig. 48). The anomalous effects of double refraction are not apparent in the smaller individuals, which remain perfectly dark between crossed nicols. Crystals as large as one or two millimeters, however, are marked by effects of this kind recalling the peculiar twinning of microcline. But they never exhibit interference colors as high as those observed on microcline, and they do not become clearly

<sup>1</sup> Areally developed like a circle, or square, or intermediate in form between the two.

light and dark four times between crossed nicols as microcline does. It is well to remember that quartz will not be found in a rock which contains either nephelite or leucite.

The pyroxenes present are especially characteristic since they will not be found so abundantly in any other lava, and they are usually absent from other lavas. These are bright emerald-green pleochroic euhedral crystals of ægirite-augite, or long tufted bright green ragged prisms of ægirite, often surrounding many

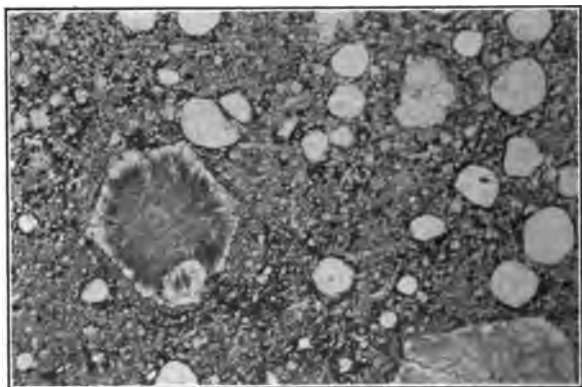


FIG. 49.—Phonolite (Leucitophyre). Olbruck. Ordinary light. The six-sided crystal is noselite. The rounded smaller white crystals are leucite. Nephelite occurs in the groundmass, but it cannot be made out in the figure.

small individuals of nephelite, or small green wisps of ægirite. (See Fig. 47.)

The occurrence of such a mineral as nephelite or leucite is of itself distinctive, but the phonolites are remarkable as well for their accessory minerals. (See Fig. 49.) These are of a kind to indicate clearly the abundance of the alkalis in the magma. Noselite, haüynite and sodalite in euhedral crystals are common. Brown garnets appear in many phonolites; and titanite, in small brown wedge-shaped crystals, is usual.

**DACITE AND ANDESITE**

**Mineralogical Composition.**—Andesine or nearly related lime-soda feldspar; biotite, hornblende, augite, diopside; as accessories magnetite, apatite, zircon. Quartz is present in dacite, but absent from andesite.

**Texture.**—Groundmass present.

The two rocks dacite and andesite are so much alike except for the presence or absence of quartz that it is sufficient for both to point out the special characteristics of andesite.

Andesite is marked by several peculiarities in the expression of its feldspar phenocrysts and by a characteristic "pepper and salt" groundmass (Fig. 3, Plate II). The plagioclase feldspar usually has some such irregular outlines as appear in the large individuals in Fig. 3, Plate II. Zonal structures are common in it. The twinning lamellæ are apt to be few and narrow and they often wedge out before running the length of the crystal. Again the feldspar will be marked by inclusions of glass zonally arranged (Fig. 3, Plate II). The groundmass, containing innumerable minute indistinguishable feldspars in a matrix much of which shows dark between crossed nicols, is best described by some such term as "pepper and salt." It is a groundmass that is not apt to appear in any other type rock in the lava series. The nearest approach to it is the groundmass of some rhyolites, but these are usually distinguishable by their content of minute pieces of quartz owing to the presence of which as the stage is turned between crossed nicols more light gets through. In andesite dull green pleochroic hornblende in long prisms marked by euhedral outlines is common. Mica may be present in rectangular squarish patches.

**DIABASE AND OLIVINE-DIABASE**

**Mineralogical Composition.**—Labradorite, bytownite, anorthite; augite; as accessories, magnetite, apatite. Olivine is present in olivine-diabase.

**Texture.**—Intermediate between those of gabbro and basalt.



**Character.**—Diabase is recognized by its structure and by its simple mineralogy. It is made up of fairly calcic lime-soda feldspar and augite, and the most noticeable thing about it is that the feldspars grew first and then augite took form in the interspaces between the feldspars (Fig. 2, Plate II). The name intersertal has been applied to this structure. The plagioclase crystals are usually euhedral, *i.e.*, bounded by good crystal outlines, or subhedral, in long lath-shaped forms. The twinning on the albite law is often marked by the development of clear-cut moderately fine lamellæ. Carlsbad twinning may often be noted in addition to the albite twinning, one part of the crystal appearing blue between crossed nicols in the  $45^\circ$  position, and the other yellowish. When such doubly twinned crystals are cut at right angles to the lamellæ then sharp hair lines bound the single bands and the crystals lend themselves to the method of determining the particular variety of plagioclase by the symmetrical extinctions, as outlined on page 52. Yellowish interference colors point to the occurrence of calcic feldspars. Labradorite is perhaps the commonest feldspar present.

The augite has not had as good a chance to develop with freely grown crystal outlines as did the feldspar. Augite individuals are tucked away in the interstices. Some will be noted filling nearly triangular spaces; or their boundaries will be quadrangular, but determined for them by the sides of the feldspars. The euhedral outline of augite so often well developed in other rocks and of value for the recognition of the mineral does not appear in diabase. Furthermore the cleavage cracks on basal sections are not commonly seen in good development. The augite of diabase is often, however, of a peculiar violet-red which the eye soon learns to recognize. (See Plate II, Fig. 2.) Another characteristic color is pale buff. Magnetite is almost sure to be found in diabase. Skeleton crystals frequently mark its occurrence. Apatite in crystals which for this mineral are large may often be noted. This assemblage of characteristics is striking. Diabase may be recognized by its peculiar structure even when

the augite has been in great part or wholly changed to chlorite and when the feldspar is so far decayed as scarcely to show the albite twinning lamellæ.

### OLIVINE-BASALT AND BASALT

**Mineralogical Composition.**—Labradorite, bytownite, anorthite; augite; magnetite. Olivine is present in olivine-basalt.

**Texture.**—A groundmass, often in part glassy, is present.

**Character.**—Basalt has in general the same chemical composition as diabase, but for it the conditions of cooling were more rapid. There is in the first place an absence of the characteristic "intersertal" structure so prominent in diabase (Fig. 2, Plate II). With very quick cooling a glassy base appears in the groundmass. This may often be richly sown with magnetite dots or skeleton crystals. The crystalline portion of the rock is made up of prominent augite and olivine crystals, with plagioclase very poorly developed in small individuals. The augite phenocrysts are often a pale buff color which is highly characteristic (Fig. 4, Plate II). The crystal outlines are usually good. At times the augite of basalt shows brilliant interference colors. Again the mineral is almost unchanged in appearance after the nicols have been crossed. Olivine is frequently euhedral. It is in olivine-basalt that we see this mineral at its best. We can readily note the parallel extinction when it shows euhedral outlines. The interference colors are brilliant. In many cases olivine is the only prominent phenocryst in a crystalline groundmass made up of somewhat indefinite brown augite individuals, and magnetite dots, with or without a poor representation of lime-soda feldspar, the determination of which is difficult. This assemblage of characteristics marks a rock type quite unlike andesite and distinct from diabase.

### CHEMICAL COMPOSITION OF TYPE ROCKS

The student may make use of the diagrams given in Fig. 50 to gain some knowledge of the chemical composition of the main

rock types. In Fig. 50, *B* is drawn to indicate the composition of the average rock. The molecular amounts of its several

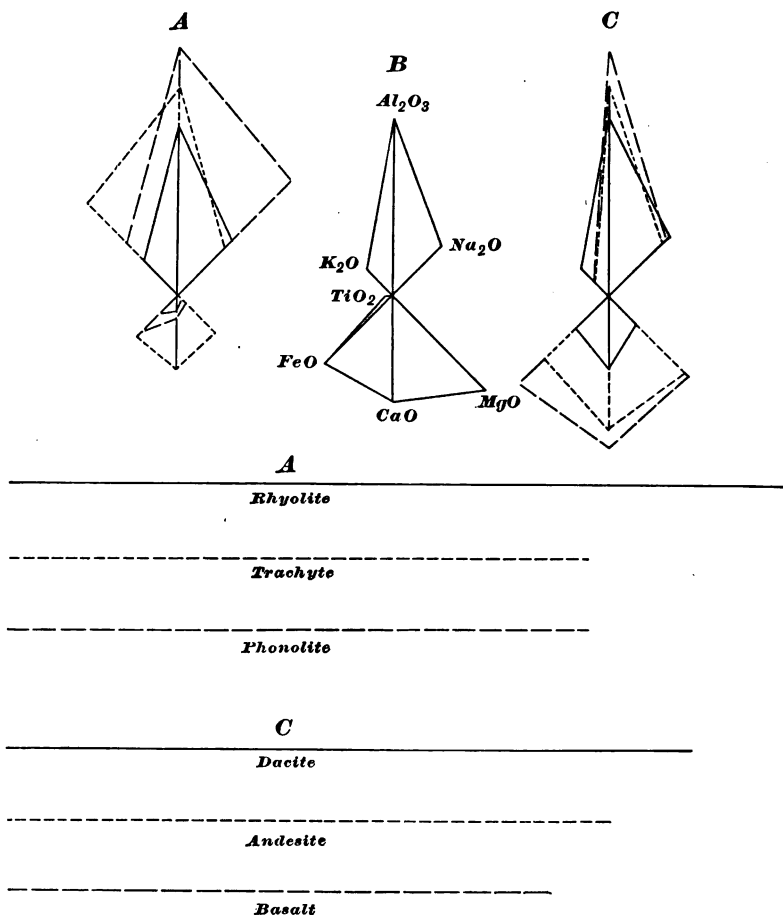
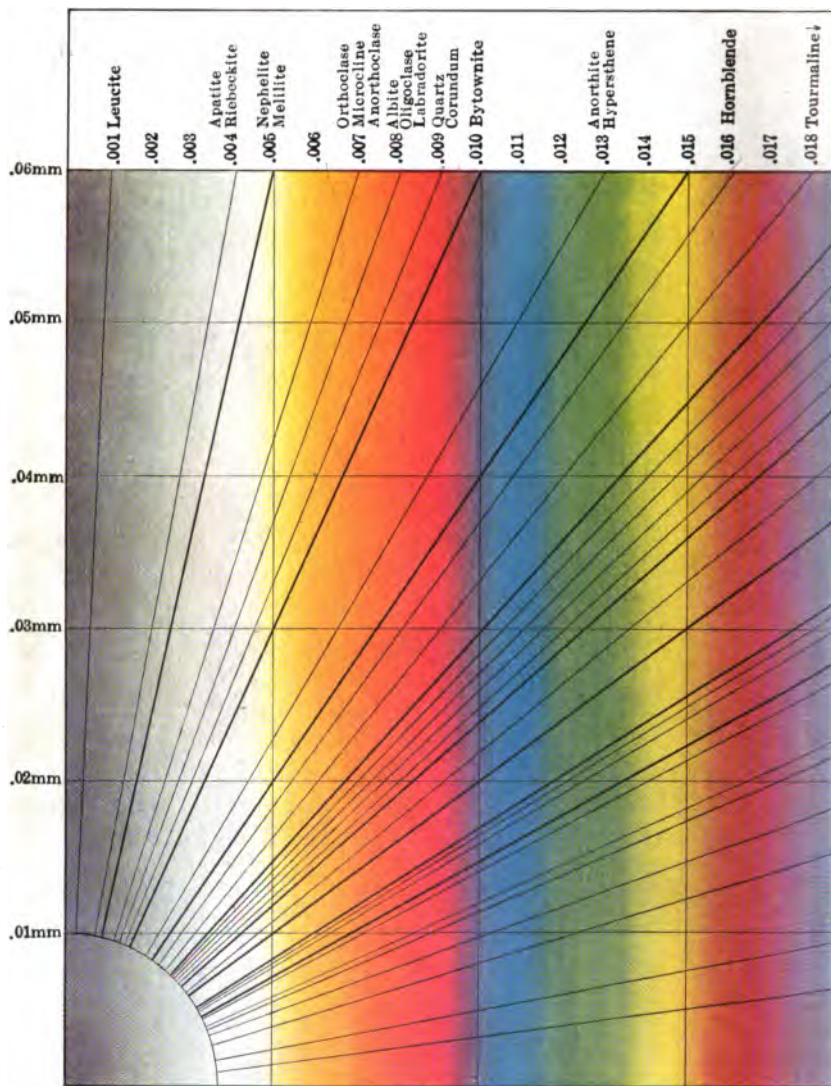


FIG. 50.—Diagrams to illustrate the chemical composition of type rocks.

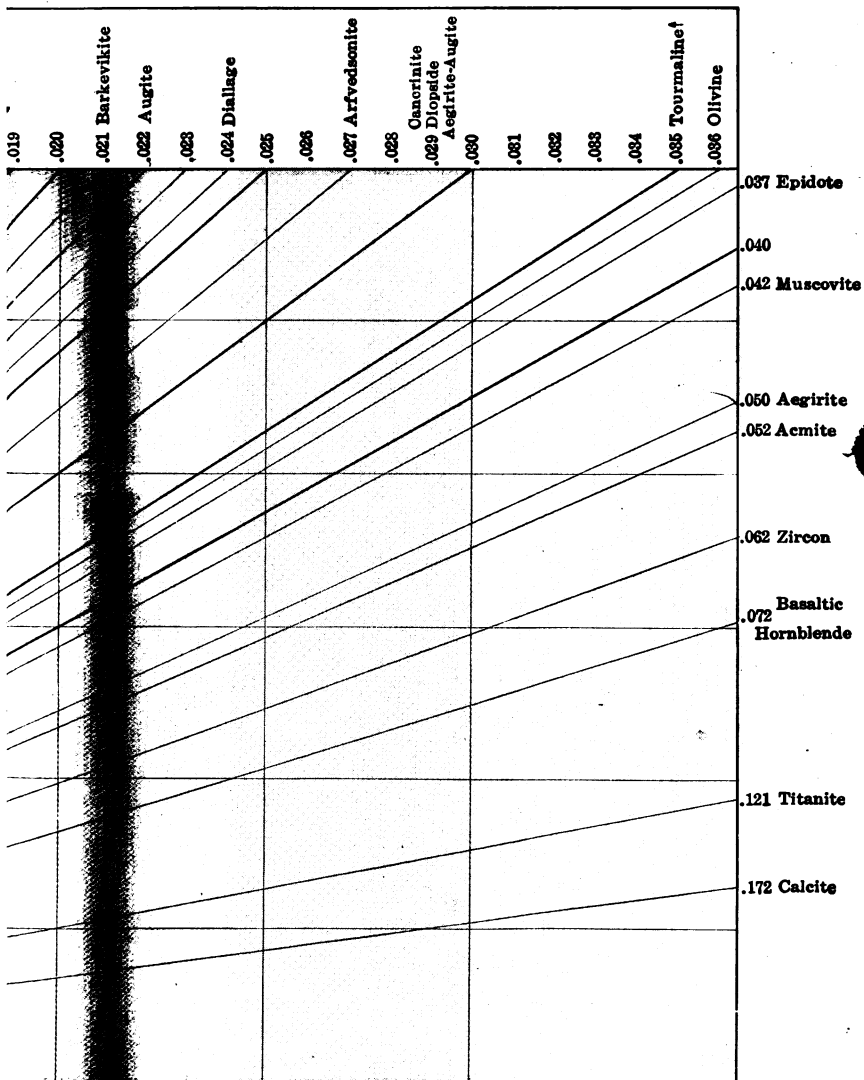
oxides are plotted along the lines against which the names of the oxides  $Al_2O_3$ ,  $K_2O$ ,  $Na_2O$ ,  $TiO_2$ ,  $FeO$ ,  $CaO$ , and  $MgO$  stand, in





First Order

Second Order



Third Order

Fourth Order







PLATE II



FIG. 1.



FIG. 2.

## PLATE II.

FIG. 1.—GRANITE, BETWEEN CROSSED NICOLS.

*(Reproduced from a drawing in water color.)*

The constituent minerals are microcline, quartz and biotite. Owing to the thickness of the section, brilliant colors of the first and second orders appear.

The feldspar (microcline) in the right hand quadrants is marked by its characteristic lattice—structure twinning. The dark brown mineral in the S. W. quadrant near the center of the figure is biotite. The drawing shows the mottled or "curly maple" appearance peculiar to the mineral in certain positions of the stage. The remaining crystals in the figure are sections of quartz cut in several crystallographic directions. Were the rock section thin, only the bluish gray shown on the piece bordering the biotite in the S. W. quadrant would appear. The red, between the quartz crystal mentioned above and the microcline, and the yellow, orange and green in the N. W. quadrant mark the range of colors which is often seen when in a thick rock section several pieces of quartz have been cut in different crystallographic directions. The quartz crystals do not show good straight cleavage cracks like those in the biotite. Some of the individuals of quartz are clear and glassy and free from inclusions. Others are marked by abundant inclusions. In ordinary light all the minerals, with the exception of the brown biotite, would be colorless.

It will be observed that the texture of the granite is altogether unlike that shown in Figs. 3 and 4, andesite and olivine-basalt, in which a ground-mass is present. In the granite, with conditions allowing for an extremely slow rate of cooling, many individuals were growing together at much the same time. They interfered with each other, and consequently there are ragged boundary lines between them. The individuals are anhedral, i. e., not bounded by crystal faces. The texture is granitoid.

FIG. 2.—DIABASE.

*(From a drawing in water-color.)*

The constituent minerals are augite and plagioclase.

The augite is represented as it would appear in ordinary light, violet-red or buff colored. These colors are highly characteristic. Surrounding the augite is plagioclase feldspar, drawn as it would appear between crossed nicols. The twinning in parallel bands on the albite law is marked.

A most important means of recognizing diabase is its structure. The plagioclase has plainly grown first, and the augite has filled in the spaces left for it between the plagioclase crystals. This structure is peculiarly characteristic of diabase.

## PLATE II.

FIG. 1.—GRANITE, BETWEEN CROSSED NICOLS.  
(Reproduced from a drawing in water color.)

The constituent minerals are microcline, quartz and biotite. Owing to the thickness of the section, brilliant colors of the first and second orders appear.

The feldspar (microcline) in the right hand quadrant is marked by its characteristic lattice—schematic twinning. The dark brown mineral in the S. W. quadrant near the center of the figure is biotite. The drawing shows the mottled or "crazy maple" appearance peculiar to the mineral in certain positions of the stage. The remaining crystals in the figure are sections of quartz cut in several crystallographic directions. Were the rock section thin, only the bluish gray brown on the surface showing the biotite in the S. W. quadrant would appear. The red between the quartz crystal mentioned above and the microcline and the yellow, orange and green in the N. W. quadrant mark the range of colors which is often seen when in a thick rock section several pieces of quartz have been cut in different crystallographic directions. The quartz crystals do not show good straight cleavage cracks like those in the biotite. Some of the individuals of quartz are clear and glassy and free from inclusions. Others are marked by abundant inclusions. In ordinary light all the minerals with the exception of the brown biotite, would be colorless.

It will be observed that the texture of the granite is altogether unlike that shown in Figs. 3 and 4, andesite and olivine-basalt, in which a ground-mass is present. In the granite, the ground-mass is absent, allowing for an extremely slow rate of cooling, many individuals are growing together at much the same time. They interlocked with each other and consequently there are ragged boundary lines between them. The microcline is anhedral, and not bounded by crystal faces. The texture is granular.

### FIG. 2.—DIABASE.

(Reproduced from a drawing in water color.)

The constituent minerals are plagioclase and diopside. The augite is represented by a small area in the upper right, violet-red or buff colored. The plagioclase is represented by the surrounding area. The augite is plagioclase having a small area in the upper right, violet-red or buff colored. The twinning in parallel bands on the augite is marked.

A most important means of recognizing diopside is its structure. The plagioclase has plainly grown first, and the augite has filled in the spaces between for it between the plagioclase crystals. This structure is peculiarly characteristic of diopside.

## PLATE II.—Continued.

Fig. 3.—ANDRESITE, CROSSED NICOLS.

(From a color photograph taken on a Lumière plate.)

The chief constituents are plagioclase and hornblende. The large crystals near the center of the figure are plagioclase. The mineral is subhedral and marked by many inclusions. The inclusions are few and interrupted. Zonal structure appears clearly in the crystal on the margin right of the figure in the S.E. quadrant. The triangular green crystal to the right of the large feldspar is hornblende. Owing to its strong absorption it does not show brilliant interference colors. The groundmass has a characteristic "paper and salt" appearance. It may look thick and dark in the illustration, or more light may come through it in thinner sections.

Fig. 4.—(Color photograph) ANDRESITE, CROSSED NICOLS.

(Photomicrograph of a thin section.)

The constituent minerals are quartz, feldspar, hornblende, and magnetite. The dull brownish color of the rock is caused by the prominence of buff or dull brown augite as a constituent of the groundmass. Plagioclase, in colorless anhedral or subhedral individuals is scarcely distinguishable. The black grains are magnetite. The prominent euhedral colorless crystal in the center of the figure is olivine. The occurrence of this mineral with abundant buff colored augite marks the rock in a striking way.

## PLATE II.—Continued.

FIG. 3.—ANDESITE, CROSSED NICOLS.

(From a color photograph taken on a Lumière plate.)

The chief constituents are plagioclase and hornblende. The large crystals near the center of the figure are plagioclase. The mineral is subhedral, and marked by many inclusions. Twinning lamellæ are few and interrupted. Zonal structure appears clearly in the crystal on the margin of the figure in the S. E. quadrant. The triangular green crystal to the right of the large feldspars is hornblende. Owing to its strong absorption it does not show brilliant interference colors.

The groundmass has a characteristic "pepper and salt" appearance. It may look thick and dark, as in the illustration, or more light may come through it in thinner sections.

FIG. 4.—OLIVINE-BASALT, ORDINARY LIGHT.

(Reproduced from a Lumière plate.)

The constituent minerals are augite, olivine, plagioclase and magnetite.

The dull brownish color of the whole rock is occasioned by the prominence of buff or dull brown augite as a constituent of the groundmass. Plagioclase, in colorless anhedral or subhedral individuals is scarcely distinguishable. The black grains are magnetite. The prominent euhedral colorless crystal in the center of the figure is olivine. The occurrence of this mineral with abundant buff colored augite marks the rock in a striking way.

PLATE II—(*Continued*)



FIG. 3.

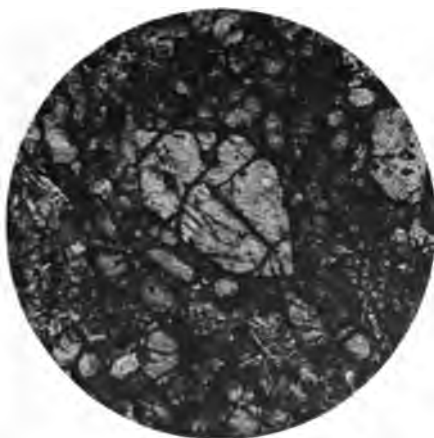


FIG. 4.



accordance with the method proposed by Iddings.<sup>1</sup> Connecting lines, as that between  $\text{Na}_2\text{O}$  and  $\text{Al}_2\text{O}_3$ , and that between  $\text{Al}_2\text{O}_3$  and  $\text{K}_2\text{O}$  are added to bound the figure and to help the eye to realize its proportions. The lengths of the horizontal lines are proportional to half the molecular amounts of the silica. The correspondence between the analyses of granite and rhyolite, syenite and trachyte, nephelite-syenite and phonolite, quartz-diorite and dacite, diorite and andesite, gabbro and basalt, is so close that the outlines plotted in Fig. 50 *A* and *C* will serve for comparison of all the type rocks in the table on page 98.

For references to the literature of the several type rocks consult H. Rosenbusch, "Massige Gesteine," 1907-8, Band II.

Granite, p. 17

Syenite, p. 129.

Nephelite-Syenite, p. 184.

Quartz-Diorite and Diorite, p. 254.

Gabbro and Olivine-Gabbro, p. 310.

Rhyolite, p. 727.

Trachyte, p. 877.

Phonolite, p. 952.

Dacite, p. 989.

Andesite, p. 1015.

Basalt and Diabase, p. 1121.

Iddings, "Igneous Rocks," Vol. I, page 17.



## CHAPTER VII

### THE VARIETAL ROCKS RELATED TO THE TYPE ROCKS

The literature of petrography is voluminous. In it are described in detail several hundred varietal rocks which may be grouped around the types considered in Chapter VI. As an aid to the student's wider reading, in the course of which he will need to compare many closely related rocks, and as a body of data for reference the tabulations of varietal rocks with numerous references to the literature, will prove serviceable. The writer has made a large use of the descriptions in Iddings, "Igneous Rocks," Vol. I, in the construction of the following rock tables. To indicate the relative frequency of occurrence of these rare rocks on the basis of 1000 a number has been placed in the tables under the name of each varietal rock. For this purpose a count was made of the rocks tabulated in the collection brought together by Dr. H. S. Washington in Professional Papers 14 and 28 of the United States Geological Survey. It will be noted that not more than about a score of the varietal rocks occur more frequently than two times in a thousand in this representative collection.

Advanced petrographic work calls for the precise determination of the constituent minerals in a rock, and for their estimation quantitatively. Unfortunately many of the rarer rocks were originally described without much regard to the giving of quantitative data bearing on the proportions of the minerals present in them. In the tables which follow the abbreviations noted below have been used to assign roughly to each mineral the part played by it in the rock.

*P* prominent, preponderant

*S* subordinate

+ occurring occasionally, or in very small amounts

An asterisk (\*) refers to the occurrence of a mineral in phenocrysts, *i.e.*, in prominent crystals in the groundmass.

When a letter is followed by the numeral 1, as S1 in the column for the rock Ekerite in the table below, it signifies that the rock contains either one or the other of the minerals against which the sign S1 stands.

### Abbreviations

Used in references to petrographic literature

A. J. S. American Journal of Science (New Haven).

Bull. Bulletin.

G. F. F. Geologiske Förening in Stockholm Förhandlingar (Stockholm).

J. G. Journal of Geology (Chicago).

N. J. Neues Jahrbuch für Mineralogie, Geologie, und Palaontologie (Stuttgart).

N. J. B. B. Neues Jahrbuch, Beilage Band (Stuttgart).

Q. J. G. S. Quarterly Journal of the Geological Society of London.

Ros. Mass. Gest. Rosenbusch, Massige Gesteine.

T. M. P. M. Tschermak's Mineralogische und Petrographische Mittheilungen (Wien).

U. S. G. S. United States Geological Survey.

Z. D. G. G. Zeitschrift der Deutsche Geologische Gesellschaft (Berlin).

Z. K. Zeitschrift für Krystallographie (München).

### THE VARIETIES OF GRANITE

The first thing taken into account in the subdivision of the granites is the amount of lime-bearing minerals present. Alkali granites on the one hand are almost without lime-bearing minerals. They carry little or no lime-soda feldspar. Among these rocks are:

**Aplite.**—Quartz and alkali feldspars; except for a little muscovite almost without subordinate minerals.

**Alaskite.**—Quartz and alkali feldspars almost entirely; without muscovite. Twentieth Ann. Rep. U. S. G. S., Part 7, 189, 195. Amer. Geol., XXV, 231.

**Riebeckite-Granite.**—Characterized by the amphibole riebeckite in subordinate amounts.

The mineralogical composition of others is tabulated below.

	(A) ALSBACHITE 1	(B) EKERITE <1	(C) ROCKALLITE <1
Quartz.....	P	P	P
Alkali feldspar....	.....	P	.....
Orthoclase.....	P	.....	.....
Albite.....	.....	.....	P
Biotite.....	S	+	.....
Arfvedsonite.....	.....	S1	.....
Ægirite-acmite ...	.....	.....	P
		Ægirite S1	Nearly equal amounts of each mineral

(A) Notizbl. Ver. Erdk. zu Darmstadt, 1892. Heft 13, 1.

(B) Ros. Mass. Gest. 525, 1907. Nyt. Magazin f. Naturvid, Bd. XLIV, Heft 2, 114. Kristiania, 1906.

(C) Trans. Roy. Irish Acad. XXI., Part III, 39. A. J. S., Mar., 1889, 241.

The **calci-alkalic granites** differ from the alkali granites in their larger content of lime-bearing minerals. Their feldspars are still preponderantly alkali feldspars but with these small amounts of lime-soda feldspar occur.

Among the **Calci-alkalic Granites** are:

**Muscovite-granite;**

**Muscovite-biotite-granite;**

**Biotite-granite, without muscovite;**

**Hornblende-biotite-granite;**

**Hornblende-granite, without biotite;**

**Pyroxene-granite, with scarcely any hornblende or biotite.**

ALKALI-SYENITES

	(A) NORD- MARKITE 2	(B) PULAS- KITE 2	(C) UMPTE- KITE 1	(D) LAURVI- KITE 1	(E) SODALITE- SYENITE 1
Quartz.....	+	.....	.....	.....	.....
Orthoclase.....	.....	P	.....	.....	P
Soda-orthoclase	P	.....	.....	.....	.....
Soda-microcline	.....	.....	.....	P	P1
Albite.....	P	.....	.....	.....	P
Microperthite..	P	.....	P	P	P1
Nephelite.....	.....	S	+	+	.....
Sodalite.....	.....	S	.....	+	S
Biotite.....	+	+	.....	+	+
Arfvedsonite...	.....	.....	+1	.....	.....
Riebeckite.....	.....	.....	+1	.....	.....
Barkevikite....	.....	+	+1	+	S
Diopside.....	.....	+	.....	S	+
Augite.....	.....	.....	.....	S	.....
Egirite-augite ..	.....	.....	.....	S	.....
Egirite.....	+	.....	.....	.....	.....
Olivine.....	.....	.....	.....	+	.....

(A) Z. K., XVI, 54, 1890.

(B) Ann. Rep. Geol. Surv. Arkansas, 1890, II, 56.

(C) Fennia, XI, 2, 1894, Ros. Mass. Gest., 151, 1907.

(D) Z. K., XVI, 29, 1890.

(E) A. J. S., Apr., 1893, 296.

## THE SYENITES AND RELATED ROCKS

The syenites like the granites fall into two divisions:

I. Alkali-Syenites, which are almost without lime-bearing minerals; and

II. Calci-alkalic syenites, which have a notable content of lime-bearing minerals.

They may be tabulated as on pages 119 and 120.

## CALCI-ALKALIC SYENITES

	MICA-SYENITE	HORNBLende-SYENITE	(A) TÖNSBERGITE < 1	(B) AKERIT < 1
Quartz.....	+	+	+	+
Orthoclase.....	P	P	P	P
Oligoclase.....	P	P	.....	P1
Andesine.....	.....	.....	P	P1
Biotite.....	S	+	.....	S
Hornblende.....	+	S	.....	.....
Diopside.....	.....	.....	.....	S2
Ægirite-augite.....	.....	.....	.....	S2

Pyroxene +

(A) Erup tivgest. d. Kirstianiageb. III, 328, 1899.

(B) Z. K., 1890, 43.





Among the variants from the syenites which are rich in ferromagnesian minerals are shonkinite and malignite. A statement of their mineralogical composition follows.

	(A) SHONKIN- ITE (in part) 1	(B) GARNET- PYROXENE- MALIGNITE < 1	(C) AMPHIBOLE- MALIGNITE < 1
Orthoclase.....	S	.....	.....
Soda-microcline.....	+	.....	.....
Albite.....	+	.....	.....
Microperthite.....	.....	P	P
Nephelite.....	+	.....	.....
Sodalite.....	+	.....	.....
Biotite.....	P	S	S
Arfvedsonite.....	.....	P	P
Augite.....	P	.....	.....
Egirite-augite.....	.....	S	S
Olivine.....	P	.....	.....
Melanite.....	.....	+	.....
Apatite.....	+ or S	+	+

(A) Bull. Geol. Soc. Amer., VI, 415, 1895. A. J. S., Dec., 1895, p. 479.

(B) }  
(C) } Bull. Dept. Geol. Univ. Calif., I, 340, 1896.



## THE NEPHELITE-SYENITES AND RELATED ROCKS

The number of phanocrystalline rocks which may be considered as varieties of the type rock nephelite-syenite is large, and, as an inspection of the inset table (1) will make plain, their constituent minerals are many. The sodic character of the magmas is their striking peculiarity.

Phanocrystalline rocks related to Nephelite-syenite, but without feldspar, composed chiefly of feldspathoids and sodic ferro-magnesian minerals, are rare. Urtite, Sussexite and Tawite are relatively poor in ferro-magnesian minerals as compared with Ijolite, Nephelinite, Missouriite and Jacupirangite. Sussexite is Urtite which shows a porphyritic texture—large phenocrysts of nephelite in a fine-grained assemblage of nephelite and ægirite.

	(A) URTITE 1	(B) TAWITE <1	(C) IJOLITE 3	(D) NEPHEL- INITE 5	(E) MIS- SOURITE <1	(F) JACUP- IRANGITE 1
Orthoclase....				+		
Lime-soda F....				+		
Nephelite....	P		P	P		S
Leucite....				+	S	
Sodalite....		P		+		
Biotite....					+	
Diopside....				P		
Augite....			P		P	P
Æg.-augite....			P	P		
Ægirite....	S			P		
Pyroxene....		P				
Olivine....				+	S	

	(A) URTITE 1	(B) TAWITE <1	(C) IJOLITE 3	(D) NEPHEL- INITE 5	(E) MIS- SOURITE <1	(F) JACUP- IRANGITE 1
Melanite.....	.....	.....	+	+	.....	.....
Apatite.....	+	.....	+	+	.....	8
Titanite.....	.....	.....	+	.....	.....	.....
	Nephelite may be over 80%. Susselite is por- phyritic Urtite.		Nephelite and pyr- oxene in nearly equal amounts.	Nephelite and pyr- oxene in nearly equal amounts. Melilite +.	Augite 50%. Olivine 15%. Leucite, 15%. Biotite, 6%. Analcite, 8%.	Magnetite P Ilmenite P.

(A) G. F. F., XVIII, 463, 1896.

(B) Fennia, XI, 2, 1894.

(C) G. F. F., 1891, 300.

(D) Ros. Mass. Gest., 1433, 1908.

(E) A. J. S., II, p. 321, 1896.

(F) A. J. S., Apr., 1891, p. 314.

## THE DIORITES AND RELATED ROCKS

The varieties of Diorite include those which, with fairly calcic feldspar, andesine or labradorite, are characterized by the presence of considerable orthoclase on the one hand, and, on the other hand, the normal non-potassic sodic Diorites in which orthoclase and microcline are very sparingly present. Kentallenite and Durbachite are very rich in ferro-magnesian minerals, and correspond in a general way to the Shonkinite-Malignite series. Olivine-Monzonite is like Kentallenite except that the feldspars and ferro-magnesian minerals are in nearly equal proportions.

Of the variants tabulated below Quartz-Monzonite is nearest to granite, while basic Quartz-Diorite approaches gabbro closely.

Granodiorite has less orthoclase than Quartz-Monzonite and more than Quartz-Diorite.

## QUARTZ-DIORITES

	QUARTZ-MONZONITE <sub>1</sub>	QUARTZ-MICA-DIORITE	QUARTZ-MICA-HORN-BLENDE-DIORITE	QUARTZ-MICA-HORN-BLENDE-DIORITE	QUARTZ-MICA-HYPHEN-DIORITE	(A) QUARTZ-AUGITE-DIORITE ANDEN-DIORITE	(B) ADAMEL-LITE <1	QUARTZ-DIORITE (basic)
Quartz.....	P	P	P	P	P	P	P	S
Orthoclase.....	S	+	+	+	+	+	+	+
Andesine.....	P	P	P	P	P	P	P	
Labradorite.....	P							P
Muscovite.....							S	
Biotite.....	Sl	P	P	+	S	+	P	Sl
Hornblende.....	Sl	+	S	P	+	S	P	Sl
Pyroxene.....	Sl	+	+	+	+	P (augite)	+	Sl
Hypersthene.....					P			
			In Tonalite the principal feldspar is per. andesine.	Quartz-Diorite pro. per.				

(A) Beiträge Geol. d. Argent. Republik, 212, 1885.

(B) N. J., 1890, I, 75.

	(A) MONZON- ITE 5	(B) AKERITE <1	DIORITE (strictly)	(C) ORNÖITE <1	(D) MALCHITE 1	(E) LUCITE 1	(F) KENTAL- LENITE <1	(G) DURBACH- ITE <1
Quartz .....		+			+			+
Orthoclase .....	S	P	+	+			P	P
Microcline .....			+	+				
Oligoclase .....			S	P				
Andesine .....	P1	P	P		P	P	P	P
Labradorite .....	P1		S					P
Nephelite .....								
Biotite .....	S2	S	+		+	+	P	P
Hornblende .....	S2		P	S	P	P		P
Diopside .....		S						
Augite .....	S2		+				P	
Ægirite .....		+						
Olivine .....							P	
	Monsonite and Akerite may be considered varieties of syenite.					Andesine more calcic than in Malchite.		

(A) Die Eruptivgesteine des Kristiansgebietes, II, 21, 1895.

(B) Z. K., 1890, 43.

(C) G. F. F., XV, 108, 1893.

(D) Ros. Mass. Gest., 634, 1907.

(E) Notisblatt Verein. f. Erdkunde, Darmstadt, 1892, 1.

(F) Q. J. G. S., LVI, 537, 1900.

(G) Mitth. d. grossh. bad. Geol. Landesanstalt, II, 233.

## GABBROIC ROCKS

	(A) ESSEXITE (in part) 2	(B) BEERBACHITE (in part) 1	ALLI- VALITE <1	HARRI- SITE <1
Orthoclase.....	+	.....	.....	.....
Labradorite.....	P	P	.....	.....
Anorthite.....	.....	.....	P	S
Nephelite.....	+	.....	.....	.....
Biotite.....	S	.....	.....	.....
Barkevikite.....	S	.....	.....	.....
Augite.....	S	.....	+	+
Diallage.....	.....	P	.....	.....
Hypersthene....	.....	S	.....	.....
Olivine.....	+	.....	P	P

(A) Bull. Essex Inst., XXIII, 146, 1891. J. G., VII, 53, 1899.

(B) Notizbl. Ver. Erdkunde, Darmstadt, 1892, Heft 13, p. 1.

## PERIDOTITES AND PYROXENITES

The Peridotites are phanocrystalline rocks made up chiefly of olivine and pyroxene. Hornblende and mica are subordinate.

The Pyroxenites are phanocrystalline rocks made up chiefly of pyroxene. Small amounts of hornblende and calcic feldspar occur, and a little olivine may be present. Of these rocks Diallagite, Enstatite and Hypersthene are severally almost wholly diallage, enstatite and hypersthene.

	(A) SAXO- NITE (B) HARTS- BURGITE 1	(C) LHER- ZOLITE 1	(D) PIC- RITE 4	HORN- BLENDE- PICRITE	(E) CORT- LAND- TITE 1	(F) SCYEL- ITE <1	MICA- PERIDO- TITE 4	(G) KIM- BER- LITE <1	(H) DUN- ITE 1	(I) ARIE- GITE 4
Biotite.....	+	.....	+	+	.....	P	P	P	.....	.....
Hornblende..	+	.....	+	P	P	P	.....	.....	.....	+
Enstatite....	P	.....	.....	.....	.....	.....	.....	.....	.....	.....
Bronzite.....	.....	P	.....	.....	.....	S	.....	.....	.....	+
Hyperssthene.....	P	.....	+	.....	S	.....	.....	.....	.....	.....
Diopside.....	P1	.....	.....	.....	.....	.....	.....	.....	.....	P1
Augite.....	P1	.....	P	S	S	.....	+	S	+	.....
Diallage.....	.....	P	.....	.....	.....	.....	.....	.....	.....	P1
Olivine.....	P	P	P	P	S	P	P	P	P	.....
Soda-calcic F.....	.....	.....	+	.....	+	.....	+	.....	.....	.....
Eulysite is Wehrite with con- siderable garnet.	Chromite.	Chro- mite.	.....	.....	.....	Chro- mite+.	Spinel+.	.....	Chro- mite+.	Gar- net+.

(A) Wadsworth, Lithological Studies, 1884, p. 85.

(B) Ros. Mass. Gest., 1887, 269.

(C) De la Méthérie, Théorie de la Terre, II, 281.

(D) Ros. Mass. Gest., 1326, 1908.

(E) A. J. S., Jan., 1886, p. 30.

(F) Q. J. G. S., 1885, 401.

(G) Geol. Magazine, 1887, 22.

(H) Geol. v. Neu Seeland, 1864, 218.

(I) Comptes Rendus, VIII, Int. Geol. Cong., 1901, 809.

## THERALITE AND RELATED ROCKS

The rare phanocrystalline rocks characterized by the feldspars andesine-labradorite or andesine, with some orthoclase, in which the feldspathoids nephelite, leucite and the sodalites are present, as well as pyroxene, amphibole, mica and olivine, in subordinate amounts, belong to the Theralite series. The Theralites are closely related to the Teschenites, but in the latter the feldspar is more calcic, labradorite. The mineralogical differences appear in the table below.

	(A) THERALITE 2	(B) ESSEXITE (in part) 2	TESCHENITE 1
Orthoclase.....		+	
Andesine.....	P	P	
Labradorite.....		S	P
Nephelite.....	P	S1	
Sodalite.....		S1	
Biotite.....	+	+	+
Barkevikitic hornblende	+	+	S
Diopside.....	S		
Augite.....	S	+	S
Ægirite-augite.....	S		
Olivine.....	+	+	
			Analcite P. Probably altered nephelite.

(A) Ros. Mass. Gest., 427, 1907. J. E. Wolff. Petrography of the Crazy Mountains, Montana, Northern Transcont. Survey, 1885.

(B) Bull. Essex. Inst., XXIII, 146, 1891. J. G., VII, 53, 1899.

## THE ROCKS RELATED TO RHYOLITE

The subdivisions of Rhyolite have to do with mineralogical composition and with texture. Furthermore, those rocks which are known to be recent geologically, or which have the appearance of being recent geologically, and show fresh unweathered minerals, have been separated as having the **Cenotypal** habit. On the other hand old lavas geologically, or those with the signs of weathering and the appearance of age have been called **Paleotypal**.

It is to be noted that Liparite, a term much used by European geologists, is equivalent to Rhyolite.

**Quartz-Porphry** is paleotypal rhyolite.

By **Lithoidite** is meant rhyolite with a stony groundmass instead of the commoner glassy groundmass. Among the rhyolites with a glassy groundmass are:

**Perlite** in which the fracture is much like the surface of a sphere; and

**Obsidian**, with conchoidal fracture.

**Nevadite** is texturally peculiar because the phenocrysts occupy more space than the groundmass which contains them. A. J. S., June, 1884, 461.

The term **Felsite** may be used to indicate paleotypal rhyolite without phenocrysts. Under the microscope the rock is seen to consist of glass, microcrystalline quartz, and alkali feldspars.

**Pitchstone**, paleotypal, is glassy with a resin-like luster.

**Tordrillite** is the cenotypal equivalent of Alaskite. Twentieth Ann. Rep. U. S. G. S., Part 7, 189, 195.

**Quartz-Bostonite** is the paleotypal equivalent of tordrillite. The mineralogical composition of other varieties of rhyolite appears below.



## VARIETIES OF RHYOLITE

Cenotypal.....	(A) PANTEL- LERITE 3	(B) COM- ENDITE <1			
Paleotypal.....			(C) GRORU- DITE 2	(D) PAIS- ANITE 1	QUARTZ- KERATO- PHYRE 5
Quartz.....	P ..	P	P	*P	P
Orthoclase.....		P	*P		
Soda-orthoclase.....				*P	
Microcline.....			*P		
Soda-microcline.....	P				P
Albite.....					P
Biotite.....		S			+
Hornblende.....		S			
Riebeckite.....		S1		S	
Arfvedsonite.....		S1		S	
Diopside.....	P				
Ægirite-augite ..	P				
Ægirite.....		P	*P		
	Groundmass stony or glassy. Quartz pheno- crysts rare.	Stony ground- mass	Ground- mass with quartz, orthoclase and ægir- ite.		Microper- thite +.

(A) Z. K., 1881, 348.

(B) Rend. Roy. Acad. Lincei. IV., 48, 1895.

(C) Z. K., XVI, 65.

(D) T. M. P. M., XV, 435.

## TRACHYTES AND RELATED ROCKS

Among the Trachytes are: 1. **Alkalic Trachytes**; and 2. **Calci-alkalic Trachytes**. In each division cenotypal and paleotypal rocks occur.

### 1

**Ægirite-Trachyte** and **Riebeckite Trachyte** so named from their prominent dark silicates, are soda-rich alkalic trachytes.

**Sölvsbergite** and **Bostonite** are alkalic paleotypal trachytes.

### 2

Among the cenotypal calci-alkalic trachytes are

**Mica-Trachyte**

**Augite-Trachyte**

**Sanidine-Oligoclase-Trachyte**

**Domite**

Paleotypal calci-alkalic trachytes include

**Mænaite**

**Rhombenporphyry**

The mineralogical composition of a number of these rocks is tabulated below.

## VARIETIES OF TRACHYTE

Cenotypal. ....	DOMITE <1			
Paleotypal. ....		(A) MÆNAITE <1	(B) SÖLVS- BERGITE 1	(C) BOSTON- ITE 3
Quartz. ....			+1	
Orthoclase (Sani- dine)	P	+		+
Microcline. ....		P	P	P
Soda-microcline. ....		P		P
Microperthite. ....		P		P
Albite. ....			P	
Oligoclase. ....	P	P		
Nephelitē. ....			+1	
Biotite. ....	+1		S	
Hornblende. ....	+1			
Arfvedsonite. ....			S2	
Augite. ....	+1			
Ægirite-augite. ....				
Ægirite. ....			S	
		Like Bostonite, but rich in oligoclase.	Katophor- ite S2	Other min- erals al- most lack- ing.

(A) Erupt. Gest. Krist., III, 207, 1899.

(B) Erupt. Gest. Krist., I, 67.

(C) T. M. P. M., 1890, 447. Bull. 107, U. S. G. S.

Trachytic rocks which are very rich in ferro-magnesian minerals have been called Lamprophyres. Their composition is as follows:

LAMPROPHYRES

(See also page 139.)

	(A) MINETTE 2	(B) VOGESITE <1
Paleotypal.....		
Orthoclase.....	S	S
Soda-microcline.....	S1	.....
Oligoclase.....	S1	+
Biotite.....	*P	.....
Hornblende.....	*P2	*P
Diopside.....	.....	*P1
Augite.....	*P2	*P1
Olivine.....	+	+
		Varieties are Hornblende-Vo- gesite, Augite- Vogesite.

(A) A. J. S., Nov., 1893, 375.

(B) Ros. Mass. Gest., 1887, 319. Ros. Mass. Gest., 1907, 677.

## THE PHONOLITE SERIES

Varieties of Phonolite are tabulated below

Cenotypal.....	(A) APACHITE <1		(C) OREN- DITE 1	(D) WYOMING- ITE 1
Paleotypal.....		(B) TIN- GUAITE 10		
Orthoclase.....		P	*P	
Microcline.....		P		
Soda-microcline ..		P		
Microperthite.....	*P	P		
Nephelite.....	*P	P		
Leucite.....		S	P	P
Sodalite.....		S		
Biotite.....		S		
Phlogopite.....			*P	*P
Arfvedsonite.....	S			
Barkevikite.....	S			
Diopside.....			S	P
Ægirite.....	S	P		
	Aenigmatite		Amphibole +	Glassy base which prob- ably con- tains alkali feldspar.

(A) T. M. P. M., XV, 454.

(B) T. M. P. M., XI, 447, 1890.

(C) A. J. S., Aug., 1897, p. 123.

(D) A. J. S., Aug., 1897, p. 120.

**Leucite-Phonolite** carries leucite in addition to nephelite.

**Leucitophyre** is a synonym for Leucite-Phonolite.

**Leucite-Tinguaite** carries leucite replacing some of the nephelite. The leucite is weathered and altered.

# NON-FELDSPATHIC PHONOLITIC ROCKS

Cenotypal.....	(A) LEUCITE 2	(B) MADUPITE <1	MELILITE-BASALT 4	(C) VENANZITE (D) EUKTOLITE <1		
Paleotypal.....					(E) MONCHIQUE 5	(F) ALNÖITE <1
Sanidine.....	+					
Nephelite.....			+			
Leucite.....	P			P		
Häüynite.....	+		+1			
Melilite.....	+		S	P		S
Biotite.....	+		+1		*S	*P1
Phlogopite.....		P		*P		
Hornblende...	+					
Barkevikitic Hornblende					*P	*P1
Diopside.....	P	P				

## NON-FELDSPATHIC PHONOLITIC ROCKS—(Continued)

Cenotypal . . . .	(A) LEUCI- TITE  2	(B) MADU- PITE  <1	MELI- LITE- BA- SALT  4	(C) VEN- AN- ZITE (D) EUK- TOLITE <1		
Paleotypal . . . . .					(E) MONCHI- QUITE 5	(F) ALNÖ- ITE <1
Augite . . . . .	P	.....	*P	.....	*P	*P
Ægirite-augite.	P	.....	.....	.....	.....	.....
Olivine . . . . .	.....	.....	*P	*P	S	*P
Melanite . . . . .	+	.....	.....	.....	.....	.....
Perovskite . . . . .	+	S	+	.....	.....	+
Chromite . . . . .	+	.....	+	.....	.....	+
		Glassy base, suppos- edly leucitic.		Few pheno- crysts.	Glassy base with com- position of analcite. Fouchite is monchi- quite with- out olivine. Ouachitite is Fouchite rich in biotite.	

(A) Ros. Mass. Gest., 1407, 1908.

(B) A. J. S., Aug., 1897, 139.

(C) Sitzungsber. k. pr. Akad. Wissensch, Berlin, VII, 110, 1889, and A. J. S., 1899, p. 399

(D) Ros. Mass. Gest. 1488, 1908.

(E) T. M. P. M., XI, 445, 1890.

(F) A. J. S., 1892, 269.

# THE DACITE SERIES

The varieties of *Dacite* include:

**Biotite-Dacite**

**Biotite-Hornblende-Dacite**

**Biotite-Hornblende-Pyroxene-Dacite**, as well as the rocks tabulated below.

## DACITES

	(A) DELLENITE	(B) VOLCANITE	(C) QUARTZ-BASALT (in part)
Cenotypal.....	<1	<1	<1
Paleotypal.....	DELLENITE- PORPHYRY <1 QUARTZ-POR- PHYRITE		
Quartz.....	P	.....	*P
Orthoclase.....	S	.....	.....
Soda-microcline.....	.....	*S	.....
Andesine.....	P	*P	*P
Biotite.....	S	.....	.....
Hornblende.....	S	.....	.....
Augite.....	S	*P	*P
Olivine.....	.....	*+	*P
	Equivalents of Q. Monzonite.	Glassy ground- mass.	Groundmass partly glassy, partly feld- spar and pyroxene.

(A) Brögger; Die Triadische Eruptionsfolge bei Predazzo, pp. 59 and 60.

(B) Bull. Geol. Soc. Amer., V, 598.

(C) A. J. S., Jan., 1887, 49.



### THE ANDESITE SERIES

The varieties of Andesite parallel in a general way those of diorite. There are potassic types and sodic types. Cenotypal and paleotypal andesites are met. **Mica-Andesite**, is the normal Andesite. The more common varieties are as follows:

**Pyroxene-Andesite**

**Augite-Andesite**

**Hypersthene-Andesite**

**Hornblende-Pyroxene-Andesite**

**Hornblende-Andesite**

**Hornblende-Mica-Andesite**

**Latite** is a general name for the effusive equivalents of monzonite. Bull. 89, U. S. G. S.

**Propylite** is paleotypal andesite in which the pyroxene is altered to hornblende or chlorite. Mem. Calif. Acad. Sci., I., 60, 1867. *Auganite* is the name proposed by A. N. Winchell for augite-andesite and for basalt. Oivine-basalt is then called simply basalt.

Other andesitic rocks are tabulated below.

**Paleotz**

**Quartz**

**Orthoclase**

**Oligoclase**

**Andesine**

**Labradorite**

**Andesine**

**Bytownite**

**Leucite**

**Biotite**

**Hornblende**

**Diopside**

**Augite**

**Hypersthene**

**Olivine**

(A)

(B)

(C)

di  
a1  
A

z6

te  
1:  
a1  
si

Certain dike rocks, among the Lamprophyres, rich in augite, hornblende, or biotite, may be put with the varieties of Andesite.

Of these rocks **Biotite-Kersantite** and **Hornblende-Kersantite** are not so common as **Biotite-Augite-Kersantite**.

**Cuselite** is Augite-Kersantite with little mica. (A.)

## LAMPROPHYRES

Cenotypal.....	(B) ABSARO- KITE 3			
Paleotypal.....		BIOTITE- AUGITE KERSAN- TITE 4	(C) SPESSAR- TITE < 1	(D) CAMPTO- NITE 8
Orthoclase.....	S (note)	+ (note)	+ (note)	.....
Andesine.....	.....	.....	.....	P
Labradorite-andesine..	P	P	P	.....
Biotite.....	S	P	.....	*P
Hornblende.....	.....	.....	P1	*P
Barkevikite.....	.....	.....	.....	+
Augite.....	*P	P	P1	*P
Olivine.....	*P	+	+	*+

Note.—Occurs as an outer shell.

(A) Ros. Mass. Gest., 503, 1887.

(B) J. G., III, 936.

(C) Ros. Mass. Gest., 532, 1896.

(D) A. J. S., 1879, XVII, 147.

### THE VARIETIES OF BASALT

The varieties of Basalt have to do with the prominence of certain minerals, as for instance hypersthene, hornblende, olivine, and quartz.

**Hypersthene-Basalt**, with hypersthene augite and olivine.

**Hornblende-Basalt**, with iron-rich hornblende.

**Quartz-Basalt**, with quartz phenocrysts in addition to the normal pyroxene and olivine.

**Olivine-Basalt**, rich in olivine, see page 138.

The feldspar is at times andesine and at times labradorite.

**Melaphyre** is paleotypal altered basalt.

**Odinite** is unusually rich in ferro-magnesian minerals as compared with the feldspars. In this rock labradorite, augite, and less frequently, hornblende, occur in a groundmass made up of feldspar and hornblende. Notizbl. Ver. Erdkunde, Darmstadt, 1892, Heft 13, page 1.

### TEPHRITE AND RELATED ROCKS

The equivalents of the Theralite-Teschenite series among the aphanitic rocks are rare. They are tabulated below.

Cenotypal.....	(A) TEPHRITE 4	(B) LEUCITE- TEPHRITE 3	(C) KULAITE 1	(D) BASANITE 4
Sanidine.....	+	.....	.....	.....
Oligoclase.....	+1	.....	.....	.....
Andesine.....	*P	P	.....	.....
Labradorite....	S1	P	.....	P
Nephelite.....	*P	S	.....	P
Leucite.....	.....	P	.....	.....
Sodalites.....	+	+	.....	P
Hornblende....	+	+	*P	.....
Barkevikitic hornblende.	.....	.....	.....	+
Augite.....	*S	S	S	S
Ægirite-augite..	*S	S	.....	S
Ægirite.....	*S	S	.....	.....
Olivine.....	+	+	*P	S
			Glassy groundmass containing, andesine, labradorite and altered leucite.	Leucite Basa- nite con- tains leucite, often in phenocrysts.

(A) N. J., 1865, 663.

(B) N. J., 1865, 663.

(C) H. S. Washington, "The Volcanoes of the Kula Basin," Privately printed, N. Y., 1894. A. J. S., Feb., 1894, p. 115.

(D) Ros. Mass. Gest., 1372, 1908.

## BASIC ERUPTIVE ROCKS

Certain basic rocks which on the one hand are related to the Pyroxenites and Peridotites, and on the other hand to the feldspathoid rocks are mineralogically as follows.

Phanero-crystalline	HORN-BLENDITE 1	(A) WEBSTER-ITE 2		
Cenotypal. ....			(B) LIMBUR-GITE 3	(C) AUGITITE 1
Nephelite. ....			+	+
Häüynite. ....			+	+
Biotite. ....	+			
Hornblende. ....	P		+	+
Pyroxene. ....	+			
Bronzite. ....		P		
Diopside. ....		P		
Augite. ....			P	P
Ægirite-augite. ....			+	+
Olivine. ....	+		P	
			Glassy base, partly feld- spathic.	Limburgite without olivine.

(A) Amer. Geol., VI, 35, 1890.

(B) Ros. Mass. Gest., 694, 1907.

(C) Verhandl. d. k.k. Geol. Reichsanst., 1882, 143.

## CHAPTER VIII

### THE METHOD OF DESCRIBING ROCKS

It is in every way desirable that descriptions of rocks should be in large measure quantitative. The series of quantitative terms proposed by Cross, Iddings, Pirsson and Washington in the *Journal of Geology*, Vol. X, page 611, and Vol. XIV, page 692, for the purposes of rock description have proven extremely useful. A very full account of them, with illustrations, may be found in Iddings' "Igneous Rocks" Vol. I, Chapter VI. It would be of the greatest possible service if the literature of rocks could be systematically re-written with the ends in view proposed by these workers. It is of enormous advantage for the students in a laboratory to make use of the same quantitative descriptive terms with precision. Reports on rocks can be written in an orderly manner, the labor of description is minimized, and the records of work done can be easily corrected. The chief gain is, however, to the student himself, who is forced to take critical account of relations obtaining among the minerals of rocks that he would not otherwise notice.

For each rock the beginner should record in writing

- I. the degree of crystallinity;
- II. the absolute size of the grain;
- III. the relation obtaining among the crystals as to their relative sizes, and, when a groundmass is present,
- IV. the amount of the groundmass as compared with the amount of the phenocrysts;
- V. the average size of the phenocrysts.

For each constituent mineral of the rock a statement should be made regarding:



- A. the degree of perfection of its crystal outline;
- B. its crystal habit;
- C. its arrangement in the rock.

Finally a quantitative estimate should be made in percentage figures giving roughly the amount of the whole rock represented in each mineral, with a statement of its amount in the phenocrysts, and as a constituent of the groundmass (when a groundmass is present.)

## I

Rocks may be:

- a. Holocrystalline, wholly crystalline, with no glass.
- b. Percrystalline, with crystals  $87\frac{1}{2}$  per cent. of the whole, or over, the remainder being glass,  $12\frac{1}{2}$  per cent. or less.
- c. Docrystalline, with crystals between  $87\frac{1}{2}$  per cent. and  $62\frac{1}{2}$  per cent.
- d. Hyalocrystalline with crystals between  $62\frac{1}{2}$  per cent. and  $37\frac{1}{2}$  per cent.
- e. Dohyaline, with crystals between  $37\frac{1}{2}$  per cent. and  $12\frac{1}{2}$  per cent.
- f. Perhyaline, with crystals  $12\frac{1}{2}$  per cent. or less.
- g. Holohyaline, wholly glassy.

## II

Rocks are:

- a. Coarse grained when on the average their crystals are over 5 mm. on the longest diameter.
- b. Medium grained when on the average their crystals are between 5 mm. and 1 mm. on the longest diameter.
- c. Fine grained, when their crystals are on the average less than 1 mm. on the longest diameter.

## III

Rocks may be spoken of as having an Equigranular Fabric, composed of crystals of like orders of magnitude, when the sizes

of the great number of crystals that give character to the fabric are areally as near together as 1 and  $2\frac{1}{4}$ , their diameters being within the limits 1 and  $1\frac{1}{2}$  (Fig. 51).

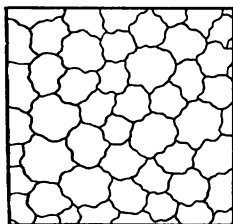
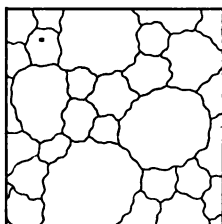
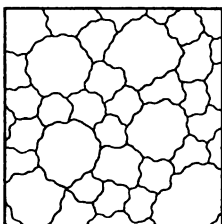


FIG. 51.—Equigranular fabric, the crystals being of the same order of magnitude.



FIGS. 52 and 53.—Inequigranular fabric, the crystals being of different orders of magnitude.

Inequigranular rocks are composed of crystals of unlike orders of magnitude (Figs. 52 and 53).

We use the terms Seriate Fabric when in inequigranular rocks the variations in the sizes of crystals are in a continuous series,

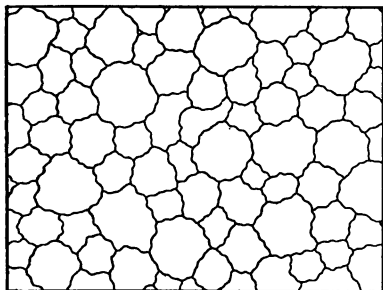


FIG. 54.—Seriate Homeoid fabric.

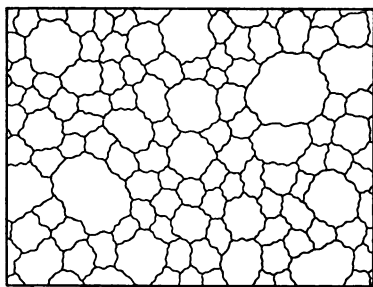


FIG. 55.—Seriate porphyroid fabric.

and Hiatal Fabric when the variations in the sizes of crystals occur in broken series, with hiatuses.

The seriate fabrics are four:

1. Seriate Homeoid, with a small range of sizes among the

crystals and nearly equal numbers of crystals of each of the different sizes (Fig. 54).

2. Seriate Porphyroid, with a small range of sizes among the crystals, and quite different numbers of crystals of different sizes (Fig. 55).

3. Seriate Intersertal, with a wide range of sizes among the crystals, and nearly equal numbers of each size (Fig. 56).

4. Seriate Porphyritic, with a wide range of sizes among the

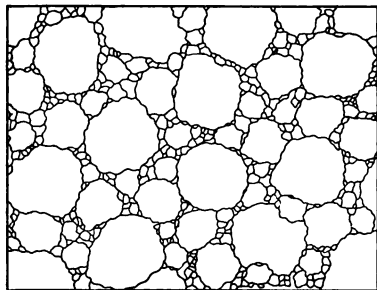


FIG. 56.—Seriate intersertal fabric.

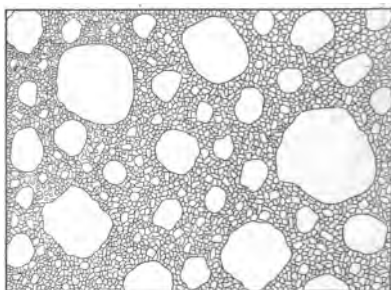


FIG. 57.—Seriate porphyritic fabric.

crystals, and marked differences in the number of crystals of each size (Fig. 57).

The hiatal fabrics are two:

1. Porphyritic, marked by a groundmass of crystals or glass in which are scattered crystals of notably larger size called phenocrysts.

2. Poikilitic, when relatively large crystals act as a matrix for smaller crystals.

#### IV

The following terms are used to state the relative proportions between the groundmass and the phenocrysts contained in it:

- a. Perpatie, groundmass  $87\frac{1}{2}$  per cent. or over.
- b. Dopatie, groundmass  $87\frac{1}{2}$  per cent. to  $62\frac{1}{2}$  per cent.

- c. Sempatic, groundmass  $62\frac{1}{2}$  per cent. to  $37\frac{1}{2}$  per cent.
- d. Dosemic, groundmass  $37\frac{1}{2}$  per cent. to  $12\frac{1}{2}$  per cent.
- e. Persemic, groundmass less than  $12\frac{1}{2}$  per cent. (See Fig. 58).

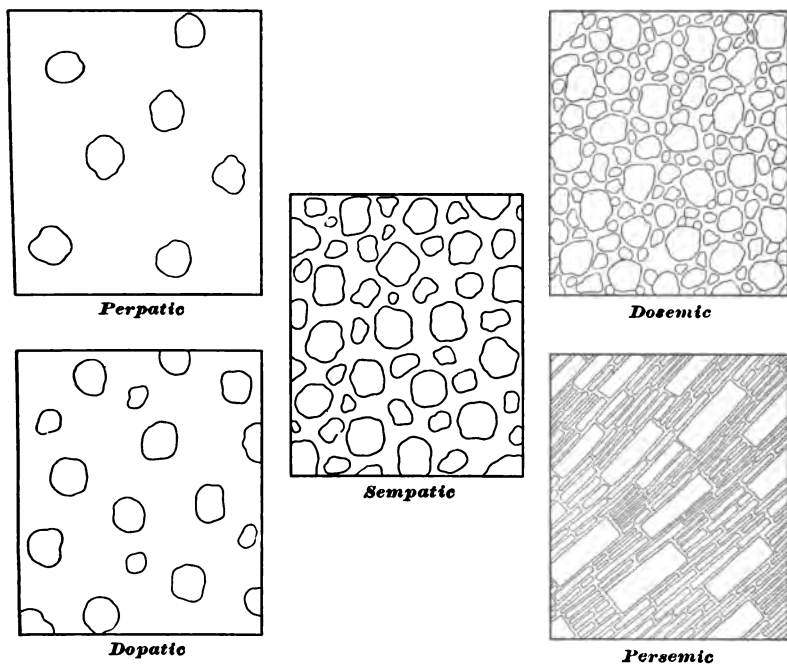


FIG. 58.—Illustrations showing the relative proportions between groundmass and phenocrysts under various conditions in rocks which have a groundmass.

## V

In describing the size of the phenocrysts we may employ the following terms:

- a. Magnophyric, when the phenocrysts are on the average greater than 5 mm. on their longest diameters.
- b. Mediophyric, when they are between 5 mm. and 1 mm.
- c. Minophyric, when they are 1 mm. or less.

## A

The descriptive terms applied to single minerals with reference to the perfection of their crystal outlines are as follows:

- a. Euhedral, completely bounded by crystal faces.
- b. Subhedral, partly bounded by crystal faces.
- c. Anhedral, without crystal faces.

## B

Various crystal habits are recorded as follows:

- a. Equant, equidimensional or nearly so.
- b. Tabular, in plates or tables. Two dimensions are relatively large as compared with the third dimension.
- c. Prismoid, when two dimensions are relatively small as compared with the third dimension.
- d. Irregular.

## C

The arrangement of tabular crystals in equigranular rocks is a. parallel, b. sub-parallel, c. diverse, lying in all directions, d. radial, divergent, e. irregular.

Of the common minerals quartz is very often anhedral, and either equant or irregular; feldspar may be tabular or prismoid; nephelite is usually euhedral and equant, or anhedral and irregular; leucite is generally subhedral and equant; mica is tabular in many rocks, and the amphiboles and pyroxenes prismoid.

## CHAPTER IX

### OUTLINE OF THE QUANTITATIVE CLASSIFICATION OF IGNEOUS ROCKS—EXAMPLES OF THE CALCULATION OF THE NORM—TABLES TO FACILITATE THE CALCULATION OF THE NORM

The chemical analysis of a rock tells us its character with final definiteness. The student of rocks cannot afford to do without the body of chemical data which Washington has assembled in Professional Papers 14 and 28 of the U. S. Geological Survey. When the analysis of a rock is available the collections referred to are invaluable for purposes of comparison. The analyses are arranged in accordance with the quantitative classification proposed by Cross, Iddings, Pirsson and Washington in "The Quantitative Classification of Igneous Rocks," The University of Chicago Press, 1903. A full account of the classification scheme may also be found in Iddings' "Igneous Rocks," Vol. I, John Wiley and Sons, New York. Tabular statements of the varieties of igneous rocks with the names proposed for them are given in the works cited above and on pages 54-59 in Professional Paper 14.

The object of the present chapter is to indicate very briefly the nature of the quantitative classification, and to give an extended series of calculated analyses to aid the beginner in getting command of the formulated method of calculation—the necessary preliminary to the placing of a rock where it belongs in the quantitative system.

The calculation as made gives the percentage weights of what are called standard minerals, for the reason that with our present knowledge it is a matter of extreme difficulty to calculate the weights of the several varieties of the micas, amphiboles and

pyroxenes. We cannot get the requisite data concerning their chemical composition by observation in rock sections, although in the case of nearly all the other rock-forming minerals we are able to do this. We are therefore forced to make our calculation in terms of the mineral molecules which make up such ferro-magnesian minerals as the micas, amphiboles and pyroxenes. The term norm applies to the mineralogical composition of the rock as calculated in this way. The calculation of the mode is the calculation of the mineralogical composition as it actually exists in the rock. This can be done when in any way, as for instance by supplementary chemical analysis of single minerals, we know the actual composition of the minerals present in the rock. As a matter of fact a very large proportion of the standard minerals used in the calculation are those actually present in the rock. In other words the correspondence between the norm and the mode is in many cases very close.

The standard minerals are arranged as on page 156 in two groups: I. salic, rich in silica and alumina; II. femic, rich in iron and magnesia. Sub-groups among these minerals are designated by the letters *F* and *L*, as will be understood from an inspection of the table of the standard minerals.

The primary division of rocks in the quantitative system is into five classes dependent upon different ratios between the salic and femic minerals as follows:

I. Persalane, with the value of the ratio of the salic minerals as compared with the femic minerals  $> 7$ .

II. Dosalane, value of  $\frac{\text{Sal}}{\text{Fem}}$  between 7 and  $1.66\frac{2}{3}$

III. Salfemane, value of  $\frac{\text{Sal}}{\text{Fem}}$  between  $1.66\frac{2}{3}$  and .6

IV. Dofemane, value of  $\frac{\text{Sal}}{\text{Fem}}$  between .6 and  $.14\frac{2}{7}$

V. Perfemane, value of  $\frac{\text{Sal}}{\text{Fem}}$  less than  $.14\frac{2}{7}$

About 95 per cent. of all igneous rocks fall into the first three classes. These classes are subdivided in exactly the same way so

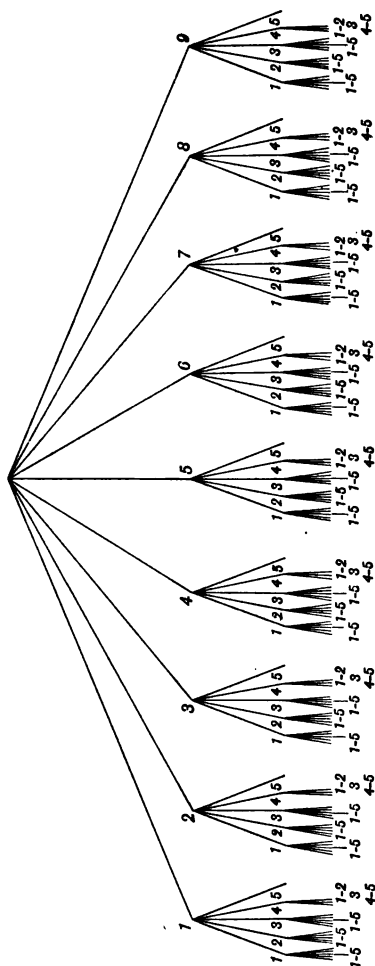


FIG. 59.—Plan of subdivision under the quantitative system. The great majority of all igneous rocks fall in Subclass I in each of the five classes. The subdivisions in Subclass I for Classes I, II and III are the same, and a similar method is used in the subdivisions of subclasses IV and V. Subclass I of Class I, II or III is divided into nine Orders. Each order is subdivided into five Rangs. Rangs 1, 2, and 3 are subdivided into five Subrangs. Rang 4 is subdivided into three Subrangs. Rang 5 is not subdivided.

that the statement of the manner in which the subdivisions of class I are made illustrates the method of subdivision for classes II



and III as well. The subdivisions of classes IV and V are slightly different from those of the first three classes but when once the method of subdivision of classes I, II, and III is understood no difficulty will arise in using tabular statements of classes IV and V. In the several classes there are subclasses, and these are divided into orders, rangs, and sub-rangs, in the manner graphically shown in Fig. 59, which will serve to illustrate the subdivisions in each of the first three classes.

In class I Persalane the sub-class I Persalone is made on the ratio between the sum of quartz, the feldspars, and the lenads'lc., ne., kp., sc., ss., taken together, and the sum of corundum and zircon. The value of the ratio  $\frac{QFL}{CZ}$  is greater than 7.<sup>1</sup> In Sub-class Persalone there are nine orders. The first four orders mark descending amounts of quartz as compared with the feldspars. In order 5 the amount of quartz or of lenads divided by the amount of feldspar is less than  $\frac{1}{7}$ . The remaining four orders are set up by fixing limits having to do with increasing amounts of lenads as against decreasing amounts of feldspars. The ratios and their values are as follows;

- Order 1.  $\frac{Q}{F}$  greater than 7
2.  $\frac{Q}{F}$  between 7. and  $1.66\frac{2}{3}$
3.  $\frac{Q}{F}$  between  $1.66\frac{2}{3}$  and .6
4.  $\frac{Q}{F}$  between .6 and  $.14\frac{2}{7}$
5.  $\frac{Q,L}{F}$  less than  $.14\frac{2}{7}$
6.  $\frac{L}{F}$  between  $.14\frac{2}{7}$  and .6

<sup>1</sup> The great majority of all known igneous rocks fall in sub-class I of each class. The other sub-classes are therefore not discussed in this chapter.

7.  $\frac{L}{F}$  between .6 and  $1.66\frac{2}{3}$

8.  $\frac{L}{F}$  between  $1.66\frac{2}{3}$  and 7

9.  $\frac{L}{F}$  over 7

The subdivision of each of the nine orders into five rangs is made on a comparison of the amount of alkalis in the salic minerals with the amount of lime in the salic minerals,  $\frac{K_2O + Na_2O}{CaO}$ , i.e., the amount of these oxides allotted to the salic minerals only, in the calculations to be considered later. The values for this ratio in each of the five rangs are the same as those used above in the first five orders.

In each of the first three rangs of each order sub-rangs are made using the same numerical limits as in the case of the rangs. The comparisons are made between the alkalis,  $\frac{K_2O}{Na_2O}$ , allotted to salic minerals, not the total amounts of these oxides, part of which are allotted to femic minerals as well. In the fourth rang of each order only three sub-rangs are made, on the same comparison of the alkalis. The limits for the values of the ratios are:

Sub-rang 1-2.  $\frac{K_2O}{Na_2O}$  greater than  $1.66\frac{2}{3}$

3.  $\frac{K_2O}{Na_2O}$  between  $1.66\frac{2}{3}$  and .6

4-5.  $\frac{K_2O}{Na_2O}$  less than .6

In rang 5 of each of the nine orders no subdivision into sub-rangs is made.

To every sub-rang, to every rang, to every order, to every subclass a name with definite significance may be given. Thus "Alsbachose" stands for a rock in sub-rang 4 of rang 2 of order 3 of

sub-class I of class I. Using all the names, Alsbachose is a sub-rang of the rang Alsbachase, a division of the order Columbare, in the sub-class Persalone, of the class Persalane. Thus the application to a rock of the name Alsbachose in this precise usage carries with it a very exact chemical connotation.

With the exception of their names all the divisions of classes II and III are like the divisions outlined above for class I. They are constituted with the same numerical limits, and the terms of comparison used in making the ratios are the same.

### EXAMPLES OF CALCULATION

For practice in calculation the collection of analyses with their norms by Dr. H. S. Washington given in Professional Papers 14 and 28 of the U. S. Geological Survey is invaluable. Of the calculated analyses which follow, all but two are taken from Professional Paper 14. By using the tables given at the end of this chapter, taken from the "Quantitative Classification of Igneous Rocks"<sup>1</sup> the arithmetical work in calculating the norms is very greatly lessened. The first set of these tables, prepared by Professor J. F. Kemp and originally published in the School of Mines Quarterly,<sup>2</sup> gives the molecular numbers for the percentage figures of the several oxides recorded in rock analyses. The second set of tables gives the percentage weights for various proportions of molecules of the standard rock-making minerals. The molecular numbers may be calculated by dividing the percentage figures for each oxide by the molecular weight of the oxide. Thus for 65.70 per cent. silica the molecular number is 1.095, the molecular weight of  $\text{SiO}_2$  being 60. The molecular number for 15.40 per cent. soda is .248, the molecular weight of  $\text{Na}_2\text{O}$  being 62. As a preliminary step in the calculation of an analysis the molecular

<sup>1</sup> Cross, Iddings, Pirsson, and Washington, *Quantitative Classification of Igneous Rocks* (Chicago: The University of Chicago Press, 1903), pp. 237-259.

<sup>2</sup> J. F. Kemp, "The Recalculation of the Chemical Analyses of Rocks," *School of Mines Quarterly*, XXVII, 75-88.

numbers for each oxide must be looked up in the tables. Small amounts of  $\text{MnO}$  (.001 to .005), and  $\text{NiO}$  are to be used as  $\text{FeO}$ ; and in the same manner small amounts of  $\text{BaO}$  and  $\text{SrO}$  are to be added in with the  $\text{CaO}$ . If  $\text{Cr}_2\text{O}_3$  does not amount to .002 it is to be added in with  $\text{Fe}_2\text{O}_3$ . For the calculation of a rock analysis we then start with the molecular proportions of the ten oxides  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{FeO}$ ,  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$ ,  $\text{TiO}_2$ , and  $\text{P}_2\text{O}_5$ , which are contained in nearly every rock, and we may also have present  $\text{ZrO}_2$ ,  $\text{SO}_3$ ,  $\text{Cl}$ ,  $\text{F}$ , and  $\text{CO}_2$ , besides  $\text{H}_2\text{O}$ ; and, in smaller amounts,  $\text{MnO}$  and  $\text{NiO}$  to be summed in with  $\text{FeO}$ ;  $\text{BaO}$  and  $\text{SrO}$ , to be added to  $\text{CaO}$ ; and  $\text{Cr}_2\text{O}_3$  which is to be counted as  $\text{Fe}_2\text{O}_3$ .  $\text{ZrO}_2$ ,  $\text{Cr}_2\text{O}_3$  in amount more than .002,  $\text{TiO}_2$ ,  $\text{P}_2\text{O}_5$ ,  $\text{SO}_3$ ,  $\text{Cl}$ ,  $\text{CO}_2$ , and  $\text{F}$ , when they are present, are first calculated as minor inflexible molecules. Their calculation as zircon, chromite, ilmenite, apatite, sodium chloride, sodium sulphate, calcite, and fluorite presents no difficulty, for the method of procedure is always the same. The eight oxides  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{FeO}$ ,  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{Na}_2\text{O}$ , and  $\text{K}_2\text{O}$  are of much greater importance in the calculation of the norm, for any one of these oxides in a given analysis is disposed of with regard to the relative quantities of the others. The difficulty in presenting to the student the method of procedure in its entirety lies in the fact that a rather long series of considerations is to be put before him at the very outset. The aim of the writer in the present chapter is to develop little by little with the aid of examples and discussions the condensed, precise statement of the authors of the "Quantitative Classification of Igneous Rocks", pages 188-196.

The simplest cases are those in which  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  are present in relatively large amounts so that they meet all claims upon them and are not exhausted.  $\text{Al}_2\text{O}_3$  remaining over is corundum, and  $\text{SiO}_2$  remaining over after all the allotments is quartz. With  $\text{SiO}_2$  present in abundance  $\text{Al}_2\text{O}_3$  may meet all the claims of  $\text{K}_2\text{O}$ ,  $\text{Na}_2\text{O}$ , and  $\text{CaO}$  upon it; or it may satisfy  $\text{K}_2\text{O}$ ,  $\text{Na}_2\text{O}$ , and part of the  $\text{CaO}$ . Again it may satisfy only  $\text{K}_2\text{O}$  and

part of the  $\text{Na}_2\text{O}$ ; or, rarely, only part of the  $\text{K}_2\text{O}$ . So the treatment varies.

The norm minerals of the two groups, which figure in the calculation, with the abbreviations for their names, and their formulas, are as follows. The table is intended to set forth the relative importance of their several rôles in the norm.

## I. SALIC GROUP

### Dominantly Siliceous and Aluminous

A. Quartz.....	$\text{SiO}_2$	Q.	
Corundum.....	$\text{Al}_2\text{O}_3$	C.	
Orthoclase.....	$\text{K}_2\text{O}.\text{Al}_2\text{O}_3.6\text{SiO}_2$	or.	F
Albite.....	$\text{Na}_2\text{O}.\text{Al}_2\text{O}_3.6\text{SiO}_2$	ab.	
Anorthite.....	$\text{CaO}.\text{Al}_2\text{O}_3.2\text{SiO}_2$	an.	
Leucite.....	$\text{K}_2\text{O}.\text{Al}_2\text{O}_3.4\text{SiO}_2$	lc.	
Nephelite.....	$\text{Na}_2\text{O}.\text{Al}_2\text{O}_3.2\text{SiO}_2$	ne.	L
Kaliophilite.....	$\text{K}_2\text{O}.\text{Al}_2\text{O}_3.2\text{SiO}_2$	kp.	
B. Minor inflexible molecules			
Sodium chloride..	$2\text{NaCl}$	sc.	
Sodium sulphate, .	$\text{Na}_2\text{SO}_4$	ss.	
Zircon.....	$\text{ZrO}_2.\text{SiO}_2$	Z.	

Of the salic minerals kaliophilite is very rare, while sodium chloride, sodium sulphate, and zircon are much less rare but still unusual.

## II. FEMIC GROUP

A. Diopside.....	$\text{CaO}.\text{(MgFe)}\text{O}.2\text{SiO}_2$	di.
Hypersthene.....	$\text{(MgFe)}\text{O}.\text{SiO}_2$	hy.
Olivine.....	$2\text{(MgFe)}\text{O}.\text{SiO}_2$	ol.
Acmite.....	$\text{Na}_2\text{O}.\text{Fe}_2\text{O}_3.4\text{SiO}_2$	ac.
Sodium metasilicate.....	$\text{Na}_2\text{O}.\text{SiO}_2$	ns.
Potassium metasilicate.....	$\text{K}_2\text{O}.\text{SiO}_2$	ks.
Wollastonite.....	$\text{CaO}.\text{SiO}_2$	wo.
Ackermanite.....	$3\text{CaO}.2\text{SiO}_2$	am.
B. Minor inflexible molecules		
Magnetite.....	$\text{Fe}_2\text{O}_3.\text{FeO}$	mt.

Ilmenite.....	$\text{FeO.TiO}_2$	il.
Chromite.....	$\text{FeO.Cr}_2\text{O}_3$	cm.
Hematite.....	$\text{Fe}_2\text{O}_3$	hm.
Titanite.....	$\text{CaO.TiO}_2.\text{SiO}_2$	tn.
Perovskite.....	$\text{CaO.TiO}_2$	pf.
Rutile.....	$\text{TiO}_2$	ru.
Apatite.....	$3\text{CaO.P}_2\text{O}_5$	$\frac{\text{CaCl}_2}{3}$ or
	$3\text{CaO.P}_2\text{O}_5$	$\frac{\text{CaF}_2}{3}$ ap.
Fluorite.....	$\text{CaF}_2$	ft.
Calcite.....	$\text{CaO.CO}_2$	cc.
Pyrite.....	$\text{FeS}_2$	pr.

Among the femic minerals diopside, hypersthene and olivine appear very often in the norm, acmite and wollastonite are not unusual, while ackermanite, potash metasilicate, and sodium metasilicate are rare. Among the minor inflexible mineral molecules magnetite, ilmenite, and apatite commonly appear; hematite, titanite, perovskite, fluorite, and pyrite are not infrequently met with; and chromite, rutile, and calcite are rare.

The minor inflexible molecules, with the exception of magnetite and hematite, will not be considered at the outset. They are not present in the first eight of the series of calculated analyses, but were they present they would claim attention in the first place. Their calculation is simple, but the form of presentation gains in clearness by bringing them in only after the main features of the calculation have been dealt with. The key to the disposal to be made of the important oxides  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{FeO}$ ,  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{Na}_2\text{O}$ , and  $\text{K}_2\text{O}$  lies in the relative affinities of  $\text{K}_2\text{O}$ ,  $\text{Na}_2\text{O}$ ,  $\text{CaO}$ ,  $\text{MgO}$ ,  $\text{FeO}$ , and  $\text{Fe}_2\text{O}_3$ , for  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ . The point of prime importance is the amount of the two oxides  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ . In the simpler cases  $\text{K}_2\text{O}$ ,  $\text{Na}_2\text{O}$ , and  $\text{CaO}$  are to be allotted to  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$  in the right proportions for the formation of the feldspars.  $\text{K}_2\text{O}$  has the strongest affinity for  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$ . It therefore has the first claim, and, after it has taken its quota of these oxides,  $\text{Na}_2\text{O}$ , with the next strongest affinity for them, receives its

quota. Lastly CaO with an affinity less than the others is to be satisfied. The oxides MgO and FeO do not unite with both  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$  at the same time in the normative minerals. They combine with  $\text{SiO}_2$  alone to form hypersthene and olivine, or with CaO and  $\text{SiO}_2$  to form diopside.

In Analysis A the simplest possible case is given.  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  are abundant, occurring in sufficient amounts to answer every claim of  $\text{K}_2\text{O}$ ,  $\text{Na}_2\text{O}$ , and CaO upon them.  $\text{Al}_2\text{O}_3$  remaining over is corundum, and  $\text{SiO}_2$  remaining over is quartz.  $\text{TiO}_2$  and  $\text{P}_2\text{O}_5$  are not present, and no other elements occur which should be calculated as the minor inflexible mineral molecules.  $\text{Fe}_2\text{O}_3$ , FeO, and MgO not being present, there is nothing to be allotted for femic minerals. In accordance with its formula  $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$ , in the proportions 1:1:6, for orthoclase,  $\text{K}_2\text{O}$ , 53, takes 53  $\text{Al}_2\text{O}_3$  and six times as much  $\text{SiO}_2$ . In the same way albite,  $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$ , in the proportions 1:1:6, with  $\text{Na}_2\text{O}$ ,

## ANALYSIS A

TOSCANOSE (APLITE). Professional Paper 14, p. 172, No. 122

Dargo, Victoria, Australia.

Percent- age <i>wt.</i>	SiO <sub>2</sub> 76.48	Al <sub>2</sub> O <sub>3</sub> 13.94	Fe <sub>2</sub> O <sub>3</sub> Trace	FeO None	MgO .01	CaO 1.08	Na <sub>2</sub> O 3.70	K <sub>2</sub> O 4.90 <i>54</i>	H <sub>2</sub> O 1.01	Sum 101.12	
Molecular Numbers <i>mols.</i>	1.275	.136				.020	.060	.053	Salic Minerals	Femic Minerals	
	318	53	.....	.....	.....	.....	.....	53	or	29.5	<i>let.</i>  <i>5</i> <i>10</i>
	360	60	.....	.....	.....	.....	60	.....	ab	31.4	
	40	20	.....	.....	.....	20	.....	.....	an	5.6	
	.....	3	.....	.....	.....	.....	.....	.....	C	.3	
	557	.....	.....	.....	.....	.....	.....	.....	Q	33.4	
NOTE.—or .053×556=29.468 written as 29.5 ab .060×524=31.440 written as 31.4 an .020×278=5.560 written as 5.6 C .003×102=.306 written as .3 Q .557×60=33.420 written as 33.4									Sal. H <sub>2</sub> O	100.2 1.01	
									Sum	101.21	

60, takes 60 molecular units of  $\text{Al}_2\text{O}_3$  and  $6 \times 60$  of  $\text{SiO}_2$ . Anorthite,  $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ , in the proportions 1:1:2, is made with 20 CaO, 20  $\text{Al}_2\text{O}_3$ , and 40  $\text{SiO}_2$ . Of  $\text{Al}_2\text{O}_3$ , 3 molecular units are left for corundum. Of  $\text{SiO}_2$ , 557 molecular units are left to form quartz. The percentage weights for the calculated minerals have been obtained from the second set of tables, pages 204–221, by looking up for orthoclase (or), the amount of  $\text{K}_2\text{O}$ , 53; for albite (ab), the amount of  $\text{Na}_2\text{O}$ , 60; for anorthite (an), the amount of CaO, 20; for corundum (C), the amount of  $\text{Al}_2\text{O}_3$ , 3. To get quartz we multiply the amount of  $\text{SiO}_2$  left over for it, (557), by 60, the molecular weight of quartz. With abundant silica, then, with  $\text{Al}_2\text{O}_3$  greater than  $\text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO}$  we make orthoclase, albite, anorthite, corundum with extra  $\text{Al}_2\text{O}_3$ , and quartz with extra  $\text{SiO}_2$ .

The sum of the percentage figures of the analysis,  $\text{H}_2\text{O}$  being 1.01, is 101.12. The sum of the calculated minerals in the norm with  $\text{H}_2\text{O}$  added in is 101.21, and for every calculated analysis these two should correspond as closely as 1 per cent. or 2 per cent. The correspondence cannot be numerically absolute, but it gives us a valuable check on the correctness of the calculation.

In Analysis B we have the same condition, except that  $\text{FeO}$  and  $\text{Fe}_2\text{O}_3$  are both present. After the allotment for the feldspars has been made, and  $\text{Al}_2\text{O}_3$  remaining over has been given to corundum (C),  $\text{Fe}_2\text{O}_3$  and  $\text{FeO}$  in the proportion 1 : 1 are allotted to magnetite (mt), and silica remaining over is quartz (Q).

The calculation of Analysis C is like the preceding one in its allotments for orthoclase (or), albite (ab), anorthite (an), corundum (C), and magnetite (mt). Then there remain over, besides  $\text{SiO}_2$ , 2 molecular units of  $\text{MgO}$ , and 15 of  $\text{FeO}$ . These are allotted to hypersthene (hy),  $(\text{MgFe})\text{O} \cdot \text{SiO}_2$ , in the proportion  $(\text{MgFe})\text{O} : \text{SiO}_2$  as 1 : 1.  $\text{MgO}$  and  $\text{FeO}$  are used in hypersthene in the ratio in which they happen to stand when this mineral comes to be made. Here the ratio is 2 : 15. In later analyses  $\text{MgO}$  and  $\text{FeO}$  will be introduced into the calculations in the minerals



## ANALYSIS B

TEHAMOSE (QUARTZ-PORPHYRY). Professional Paper 14, p. 132, No. 10  
Tamaya, Chile

Percent- age {	SiO <sub>2</sub> 75.93	Al <sub>2</sub> O <sub>2</sub> 13.26	Fe <sub>2</sub> O <sub>3</sub> 1.47	FeO .68	MgO None	CaO 1.11	Na <sub>2</sub> O 3.13	K <sub>2</sub> O 3.19	H <sub>2</sub> O .44	CO <sub>2</sub> .51	Sum 99.72
Molecular Numbers	1.266	.130	.009	.010		.020	.050	.034	Salic Minerals	Femic Minerals	
204	34							34	or	18.9	
300	50						50		ab	26.2	
40	20					20			an	5.6	
	26								C	2.7	
		9	9								mt 2.1
722									Q	43.3	
NOTE.—1 FeO neglected.									Sal. 96.7 Fem. 2.1 H <sub>2</sub> O .44 CO <sub>2</sub> .51	Fem. 2.1	
									Sum 99.75		

diopside (di), and olivine (ol), as well as in hypersthene. When all three or any two of them are to be made MgO and FeO are to stand in all of them in the same proportion in which they were used in the first of these minerals calculated at the time. In Analysis C it will be noted that hypersthene is the sum of two parts, MgO.SiO<sub>2</sub> and FeO.SiO<sub>2</sub>, each of which is to be found separately. FeO.SiO<sub>2</sub> may be looked up in the table on page 212. MgO.SiO<sub>2</sub> is equal to 100 times the amount of MgO. These findings are added together for hypersthene.

In Analysis D after the allotment for magnetite (mt), 3 molecular units of Fe<sub>2</sub>O<sub>3</sub> are left over. These go in as hematite (hm). Then MgO, 4, and FeO, 0, are left over. They are used to make a hypersthene free from FeO. In like manner in other analyses hypersthene might be made of FeO.SiO<sub>2</sub>, the other component MgO.SiO<sub>2</sub> not being available.

## ANALYSIS C

ALASKA (RHYOLITE) Professional Paper 14, p. 130, No. 1.  
Madison Plateau, Yellowstone National Park

Percentage	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	H <sub>2</sub> O	Sum
	75.19	13.77	.61	1.37	.09	.68	3.83	3.33	.65	99.83
Molecular Numbers	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	Salic Minerals	Femic Minerals
	1.253	.135	.004	.019	.002	.012	.061	.035		
	210	35						35	or 19.5	
	366	61					61		ab 32.0	
	24	12				12			an 3.3	
		27							C 2.8	
			4	4						mt .9
				15	2					hy 2.2 { MgO.SiO <sub>2</sub> .200 FeO.SiO <sub>2</sub> 1.98
	17									
	636								Q 38.2	
									Sal. 95.8	Fem. 3.1
									Fem. 3.1	
									H <sub>2</sub> O .65	
									Sum 99.55	

In analysis E the allotments are made for orthoclase (or), albite (ab), anorthite (an), and magnetite (mt). CaO remaining is allotted, with MgO, FeO, and SiO<sub>2</sub>, to diopside (di), CaO-(MgFe)O.2SiO<sub>2</sub>, the proportions of the constituents by the formula being 1:1:2. MgO and FeO together are equal to CaO, and are used in the proportion in which they are found when the mineral comes to be made. Here the ratio is 36:5, or nearly 7:1. The silica is twice the lime. MgO and FeO remaining are used for hypersthene (hy), still in the same ratio 7:1 (see page 159, line 32). SiO<sub>2</sub> is allotted to hypersthene in amount equal to MgO+FeO.

It is to be noted that we cannot have diopside and corundum together in the norm.

Analysis F presents the case where K<sub>2</sub>O is allotted with Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> to orthoclase (or), and Na<sub>2</sub>O is allotted to Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> for albite (ab). Al<sub>2</sub>O<sub>3</sub> remaining, 9 units, can satisfy only 9 units of CaO for anorthite (an). Then CaO remaining is allotted to diopside (di), as far as MgO and FeO are available. Of CaO 27 molecular units are still left. These take an equal amount of SiO<sub>2</sub> for wollastonite (wo), CaO.SiO<sub>2</sub>, 1:1. It is clear that since MgO and FeO were not present in sufficient amounts to make diopside with all the lime, there remain none of these constituents for hypersthene or olivine. So then with wollastonite there will be no hypersthene or olivine.

We now come to Analysis G, in which with abundant SiO<sub>2</sub>, the Al<sub>2</sub>O<sub>3</sub> covers K<sub>2</sub>O and partly covers Na<sub>2</sub>O. Orthoclase (or), is made, and albite (ab), as far as the Al<sub>2</sub>O<sub>3</sub> admits of it. Soda, Na<sub>2</sub>O, 5 units, left over, there being no Al<sub>2</sub>O<sub>3</sub> available for it, takes Fe<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> for acmite (ac), Na<sub>2</sub>O.Fe<sub>2</sub>O<sub>3</sub>.4SiO<sub>2</sub>, in the proportions, 1:1:4. It is clear that with acmite there will be no anorthite. After the allotment is made for magnetite (mt), the CaO takes MgO, FeO, and SiO<sub>2</sub> for diopside (di). The remaining MgO and FeO are used for hypersthene (hy), in the same proportion in which they stood for diopside.

ANALYSIS D

MAGDEBURGSE (GRANITE). Professional Paper 14, p. 124, No. 3  
Felch Mountain, Mich.

Percentage	{	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	H <sub>2</sub> O	Sum	Femic Minerals
		76.10	12.95	.65	.09	.14	.12	2.36	6.50	.65	99.65	
Molecular Numbers	{	1.268	.127	.004	.001	.004	.002	.038	.069	Salic Minerals		Femic Minerals
		414	69						69	or	38.4	
		228	38					38		ab	19.9	
		4	2				2			an	.6	
			18							C	1.8	
				1	1							mt .2
				3								hm .5
		4			0	4						hy .4 { MgO.SiO <sub>2</sub> .400 FeO.SiO <sub>2</sub> .00
		618								Q	37.1	
										Sal.	97.8	Fem. 1.1
										Fem.	1.1	
										H <sub>2</sub> O	.65	
										Sum	99.55	

## ANALYSIS E

TOSCANOSE (GRANITE). Professional Paper 14, p. 168, No. 92.  
Riesengebirge, Silesia

Percentage	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	H <sub>2</sub> O	Sum
{	71.53	13.55	1.20	.88	1.45	3.21	2.61	3.95	1.75	100.13
Molecular Numbers	1.192	.133	.007	.012	.036	.057	.042	.042	Salic Minerals	Femic Minerals
252	42							42	or	23.4
252	42						42		ab	22.0
98	49					49			an	13.6
			7	7						mt 1.6
										di 1.8
16			1	1	7	8				CaO.SiO <sub>2</sub> .93
										MgO.SiO <sub>2</sub> .700
33			4	4	29					FeO.SiO <sub>2</sub> .13
										MgO.SiO <sub>2</sub> 2.900
										FeO.SiO <sub>2</sub> .53
541									Q	32.5
									Sal.	91.5
									Fem.	6.8
									H <sub>2</sub> O	1.75
									Sum	100.05

ANALYSIS F  
ALASKOSE (GRANITE). Professional Paper 14, p. 126, No. 4.  
Waushara, Wis.

Percentage	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	H <sub>2</sub> O	Sum	
{	74.62	10.01	3.85	1.72	.33	2.43	3.33	3.38	.24	99.91	
Molecular Numbers	1.244	.098	.024	.024	.006	.043	.053	.036	Salic Minerals	Femic Minerals	
216	36								or	20.0	
318	53						53		ab	27.8	
18	9					9			an	2.5	
			24	24							mt 5.6
											di 1.7
16				0	8	8					wo 3.0
26						26					
650									Q	39.0	
									Sal.	89.3	
									Fem.	10.3	
									H <sub>2</sub> O	.24	
									Sum	99.84	
											Fem. 10.3

Analysis H presents the case in which after making orthoclase (or), albite (ab), and acmite (ac),  $\text{Na}_2\text{O}$  still remains over. This is allotted with  $\text{SiO}_2$  to form sodium metasilicate (ns),  $\text{Na}_2\text{O} \cdot \text{SiO}_2$ , 1:1. It is rarely found necessary to introduce sodium metasilicate in this way.

Case I presents the inflexible mineral molecules ilmenite, titanite, apatite, and fluorite. Sodium metasilicate is introduced, and potassium metasilicate (ks),  $\text{K}_2\text{O} \cdot \text{SiO}_2$ , as well—an extremely rare occurrence. The minor inflexible molecules in the femic group are magnetite, chromite, hematite, ilmenite, titanite, perovskite, rutile, apatite, fluorite, calcite, and pyrite. Magnetite and hematite have been introduced in preceding analyses; chromite is made in Analysis S, perovskite in Analysis S, rutile is considered in the present analysis, calcite appears in Analysis O, and pyrite in Analysis K. In the salic group we have the minor inflexible molecules zircon, sodium chloride, and sodium sulphate. Zircon appears in Analysis M, and sodium chloride and sodium sulphate in Analysis O.

Following the order stated on page 188, sec. 3, in the "Quantitative Classification of Igneous Rocks,"  $\text{Cr}_2\text{O}_3$  not being present, we first allot  $\text{FeO}$  to  $\text{TiO}_2$  for ilmenite (il), in the proportion 1:1.  $\text{TiO}_2$  remaining over takes  $\text{CaO}$  and  $\text{SiO}_2$  for titanite (tn),  $\text{CaO} \cdot \text{TiO}_2 \cdot \text{SiO}_2$ , in the proportion 1:1:1.<sup>1</sup> We are working with an analysis in which the amount of  $\text{SiO}_2$  is sufficient to meet all claims upon it. If silica were not abundant  $\text{TiO}_2$  remaining over after the allotment for ilmenite would take  $\text{CaO}$  for perovskite (pf),  $\text{CaO} \cdot \text{TiO}_2$ , in the proportion 1:1. Such a case is given in Analysis S. Here if  $\text{TiO}_2$  after the allotments for ilmenite and titanite still remained over, it would be considered as rutile (ru),  $\text{TiO}_2$ . In the next place  $\text{P}_2\text{O}_5$  takes  $3\frac{1}{2}$  times as many units of  $\text{CaO}$  as there are units of  $\text{P}_2\text{O}_5$ , and  $\frac{1}{2}$  as much F or Cl, for apatite (ap),  $3\text{CaO} \cdot \text{P}_2\text{O}_5 + \frac{\text{CaCl}_2}{3}$  or  $3\text{CaO} \cdot \text{P}_2\text{O}_5 + \frac{\text{CaF}_2}{3}$  in the ratio  $\text{CaO} : \text{P}_2\text{O}_5$  as  $3\frac{1}{2} : 1$ , and F or Cl, to satisfy  $\text{CaO}$ , equal to  $\frac{1}{3}\text{P}_2\text{O}_5$ .

<sup>1</sup> See J. G., xx., 558, and p. 191, this text.





ANALYSIS H  
VARINGOSE (PANTELLERITE). Professional Paper 14, p. 218, No. 4  
Pantelleria

Percentage	SiO <sub>2</sub> 70.30	Al <sub>2</sub> O <sub>3</sub> 6.32	Fe <sub>2</sub> O <sub>3</sub> 9.23	FeO 1.40	MgO .89	CaO .84	Na <sub>2</sub> O 7.70	K <sub>2</sub> O 2.50	H <sub>2</sub> O .82	Sum 100.00
Molecular Numbers	1.172	.062	.058	.019	.022	.015	.124	.026	Salic Minerals	Femic Minerals
	156	26	.....	.....	.....	.....	.....	26	or 14.5	
	216	36	.....	.....	.....	.....	36	.....	.....	ac 26.8
	232	.....	58	.....	.....	.....	58	.....	.....	ns 3.7
	30	.....	.....	.....	.....	.....	30	.....	.....	.....
	30	.....	.....	7	8	15	.....	.....	.....	CaO.SiO <sub>2</sub> 1.74 MgO.SiO <sub>2</sub> .800
	26	.....	.....	12	14	.....	.....	.....	.....	FeO.SiO <sub>2</sub> .92
	482	.....	.....	.....	.....	.....	.....	.....	.....	MgO.SiO <sub>2</sub> 1.400
	.....	.....	.....	.....	.....	.....	.....	.....	Q 28.9	FeO.SiO <sub>2</sub> 1.58
	.....	.....	.....	.....	.....	.....	.....	.....	Sal. 62.3	Fem. 37.0
	.....	.....	.....	.....	.....	.....	.....	.....	Fem. 37.0	.....
	.....	.....	.....	.....	.....	.....	.....	.....	H <sub>2</sub> O .82	.....
	.....	.....	.....	.....	.....	.....	.....	.....	Sum 100.12	.....

ANALYSIS I  
ORENDOSE (ORENDITE). Professional Paper 14, p. 312, No. 2  
Leucite Hills Wyom.

Percentage {	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	Cl	F	H <sub>2</sub> O	Sum	Femic Minerals
	54.08	9.49	3.19	1.03	6.74	3.55	1.39	11.76	2.08	1.35	.04	.49	3.50	99.76	
Molecular Numbers	.901	.093	.020	.014	.169	.063	.022	.125	.026	.009	.001	.026			Salic Minerals
				14					14						il 2.1
12						12			12						tn 2.4
						30				9	1				ap 3.0
						13						26			ft 1.0
558	93							93					or	51.7	ks 4.9 <sup>1</sup>
32								32							ac 9.2
80			20				20								ns .2
2							2								CaO.SiO <sub>2</sub> .93
16				0	8	8									MgO.SiO <sub>2</sub> .800
161				0	161										FeO.SiO <sub>2</sub> .00
40															MgO.SiO <sub>2</sub> 16.100
													Q	2.4	FeO.SiO <sub>2</sub> .00
													Sal.	54.1	Fem. 40.6
													Fem.	40.6	
													H <sub>2</sub> O	3.50	
													Sum	98.20	

<sup>1</sup> NOTE.—The molecular weight of ks, K<sub>2</sub>O.SiO<sub>2</sub>, is 154.

In the next place fluorine ( $F=26$ ), takes  $\frac{1}{2}$  as much  $\text{CaO}$  for fluorite (ft),  $\text{CaF}_2$ . After these minor inflexible molecules have been adjusted  $\text{K}_2\text{O}$  is allotted for orthoclase with the available  $\text{Al}_2\text{O}_3$ , 93, and  $\text{SiO}_2$ . The  $\text{K}_2\text{O}$  remaining over is allotted to potassium metasilicate (ks),  $\text{K}_2\text{O}.\text{SiO}_2$ , in the ratio 1:1. After all the  $\text{K}_2\text{O}$  has been used  $\text{Na}_2\text{O}$  takes  $\text{Fe}_2\text{O}_3$ , as far as  $\text{Fe}_2\text{O}_3$  is available (there being no  $\text{Al}_2\text{O}_3$  left to unite with it), and  $\text{SiO}_2$ , for acmite.  $\text{Na}_2\text{O}$  still remaining over is sodium metasilicate.  $\text{CaO}$  remaining after the foregoing assignments takes  $\text{MgO}$  and  $\text{FeO}$  in the requisite amounts, and in the ratio in which they stand, 8:0, for diopside (di).  $\text{MgO}$  remaining, there being no  $\text{FeO}$ , is allotted to hypersthene, and the  $\text{SiO}_2$  which has not been used is quartz.

All the analyses thus far presented, from A to I inclusive, have been those in which  $\text{SiO}_2$  is abundant. The calculation of analyses in which  $\text{SiO}_2$  is relatively low is usually more difficult. Orthoclase (or),  $\text{K}_2\text{O}.\text{Al}_2\text{O}_3.6\text{SiO}_2$ , requires more silica than leucite (lc),  $\text{K}_2\text{O}.\text{Al}_2\text{O}_3.4\text{SiO}_2$ , and leucite requires more silica than kaliophilite (kp),  $\text{K}_2\text{O}.\text{Al}_2\text{O}_3.2\text{SiO}_2$ . In the same way albite (ab),  $\text{Na}_2\text{O}.\text{Al}_2\text{O}_3.6\text{SiO}_2$ , requires more silica than nephelite (ne),  $\text{Na}_2\text{O}.\text{Al}_2\text{O}_3.2\text{SiO}_2$ . It should be noted that the ratio between  $\text{K}_2\text{O}$  and  $\text{Al}_2\text{O}_3$  is always as 1:1 in orthoclase, leucite, and kaliophilite, and that the ratio between  $\text{Na}_2\text{O}$  and  $\text{Al}_2\text{O}_3$  is always 1:1 in albite and nephelite. Hypersthene (hy),  $(\text{MgFe})\text{O}.\text{SiO}_2$ , requires more silica than olivine (ol),  $2(\text{MgFe})\text{O}.\text{SiO}_2$ , for the same amount of  $(\text{MgFe})\text{O}$ . With low silica, therefore, a substitution is made of one or more minerals which require less silica than the minerals employed in the straightforward calculations thus far considered.

Where silica is low the simplest adjustment is that illustrated by Analysis J. Here the minor inflexible molecules, ilmenite (il), and apatite (ap), are first calculated. In this analysis apatite cannot get its quota of Cl or F, for these elements have not been determined. The molecular weight is, however, taken as 336, and the percentage weight of the mineral obtained by

multiplying the amount of  $P_2O_5$  by 336. The table on page 219 for the percentage weights of apatite is based on a molecular weight of 336, F or Cl having been available.  $Al_2O_3$  is present in sufficient amount to allow with silica for the formation of orthoclase (or), albite (ab), and anorthite (an). After the allotments for magnetite (mt), and diopside (di), there remain of MgO 67, and of FeO 20 units. The silica available at this point is 62. This is not enough to make hypersthene with the MgO and FeO, for which 87 molecular units of  $SiO_2$  would be needed. If we should take the MgO and FeO with silica for olivine (ol),  $2(MgFe)O.SiO_2$ , in the proportion 2:1, then silica would be left over in amount equal to 18 units. The formulated method for calculating the norm does not admit of our making olivine at this point with  $(MgFe)O$  and silica, and then calling the remaining silica quartz. This accords with the fact that quartz and olivine are very rarely found together in igneous rocks. What we do is to divide the MgO, FeO, and available silica between hypersthene and olivine, making use of two simple algebraic equations.

$$\begin{aligned}
 &\text{Let } x = \text{the number of hypersthene molecules} \\
 &\quad \text{and } y = \text{the number of olivine molecules;} \\
 &\text{then } x + y = \text{the number of units of } (MgFe)O \\
 &\quad \text{and } x + \frac{y}{2} = \text{the number of units of } SiO_2, \\
 &\quad \text{or } x + y = 87, \\
 &\quad \text{and } x + \frac{y}{2} = 62 \\
 &\quad \quad \frac{y}{2} = 25 \\
 &\quad \quad y = 50 = \text{molecules of olivine} \\
 &\quad \text{and } x = 37 = \text{molecules of hypersthene.}
 \end{aligned}$$

MgO and FeO are to be introduced in hypersthene and in olivine in the same ratio in which they were used in diopside. The ratio in this case is 20 : 67 or, nearly, 1 :  $3\frac{1}{3}$ .

It is to be noted in connection with the use of the tables that olivine is the sum of two parts,  $2MgO.SiO_2$  and  $2FeO.SiO_2$ . We





look up the first of these on page 214 and use in looking it up one-half the amount of MgO units, i.e.,  $\frac{39}{2}$  not 39.; and in the same way we look up one-half the amount of FeO units, or  $5\frac{1}{2}$ , not 11, on page 216 and add our findings together for olivine.

Analysis K illustrates the same points as J, but in it pyrite is introduced, FeS<sub>2</sub> having been present in the rock.

$$\begin{aligned} x &= \text{the number of hypersthene molecules} \\ y &= \text{the number of olivine molecules} \\ x + y &= 137 = (\text{MgFe})\text{O} \\ x + \frac{y}{2} &= 76 = \text{SiO}_2 \\ \frac{y}{2} &= 61, y = 122, \text{ and } x = 15. \end{aligned}$$

It is to be noted that with quartz we will not have olivine in the norm and *vice versa*.

By making some hypersthene and some olivine, therefore, we can allow for a small shortage of SiO<sub>2</sub>. If we attempt to calculate Analysis L in the same manner it is found that after making orthoclase (or), albite (ab), anorthite (an), magnetite (mt), diopside (di), and olivine (ol), 219 more units of silica have been called for than are available. The silica deficit is too great to be treated as in the preceding example.

In the tentative distribution albite (ab) calls for  $6 \times 125$ , or 750, SiO<sub>2</sub>. Nephelite would use up only 250, or  $2 \times 125$ , SiO<sub>2</sub>. If we allot in the first place (holding out the soda, Na<sub>2</sub>O, 125, and equal Al<sub>2</sub>O<sub>3</sub>, 125) the proper amounts of the various oxides for orthoclase (or), anorthite (an), magnetite (mt), diopside (di), and olivine (ol), we shall have 531 units of SiO<sub>2</sub> left, to go with the 125 Na<sub>2</sub>O and 125 Al<sub>2</sub>O<sub>3</sub>. What we do then is to make a certain amount of albite and a certain amount of nephelite. It is to be remembered that in any allotment of Na<sub>2</sub>O and Al<sub>2</sub>O<sub>3</sub> to albite (ab), Na<sub>2</sub>O.Al<sub>2</sub>O<sub>3</sub>.6SiO<sub>2</sub>, and nephelite (ne), Na<sub>2</sub>O.Al<sub>2</sub>O<sub>3</sub>.2SiO<sub>2</sub>, the ratio of Na<sub>2</sub>O to Al<sub>2</sub>O<sub>3</sub> will be as 1:1. Being silica poor we made olivine (ol), with (MgFe)O and not hypersthene.

ANALYSIS L. TENTATIVE

LAURDALOSE (SYENITE-PEGMATITE). Professional Paper 14, p. 296, No. 14  
Stoksund, Norway

Percent- tage	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	H <sub>2</sub> O	Sum	
	53.81	19.69	6.20	3.63	.085	1.73	7.77	4.58	1.52	99.78	
Molecular Numbers											
	.897	.193	.039	.050	.021	.031	.125	.049	Salic Minerals		Femic Minerals
	294	49	.....	.....	.....	.....	.....	49	or	.....	.....
	750	125	.....	.....	.....	.....	125	.....	ab	.....	.....
	38	19	.....	.....	.....	19	.....	.....	an	.....	.....
	.....	.....	39	39	.....	.....	.....	.....	.....	.....	mt
	24	.....	.....	4	8	12	.....	.....	.....	.....	di
	10	.....	.....	7	13	.....	.....	.....	.....	.....	ol
	1.116 SiO <sub>2</sub> have been allotted at this point.										
	897 available SiO <sub>2</sub>										
	219 SiO <sub>2</sub> deficit for this distribution										

The formulas for the distribution of Na<sub>2</sub>O, Al<sub>2</sub>O<sub>3</sub>, and SiO<sub>2</sub> between albite and nephelite are as follows:

$$\begin{aligned}
 &\text{Let } x = \text{the number of albite molecules} \\
 &\text{Let } y = \text{the number of nephelite molecules} \\
 &\text{then } x + y = \text{Na}_2\text{O} = \text{Al}_2\text{O}_3 \\
 &\text{and } 6x + 2y = \text{SiO}_2 \\
 &\quad x + y = 125 \\
 &\quad 6x + 2y = 531 \\
 &\quad 2x + 2y = 250 \\
 &\text{subtracting, } 4x = 281 \\
 &\quad x = 70 \text{ molecules of albite} \\
 &\quad y = 55 \text{ molecules of nephelite.}
 \end{aligned}$$

It is clear that with nephelite in the norm we shall not have quartz.

Analysis M proceeds on the same lines as L except that the minor inflexible molecule zircon (Z), is first introduced, taking  $\text{ZrO}_2 = \text{SiO}_2$  in accordance with its formula  $\text{ZrO}_2 \cdot \text{SiO}_2$ .



ANALYSIS L  
LAURDALOSE (SYENITE-PAGMATITE). Professional Paper 14, p. 296, No. 14  
Stoksaund, Norway

Percentage	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	Na <sub>2</sub>	K <sub>2</sub> O	H <sub>2</sub> O	Sum	
{	53.81	19.69	6.20	3.63	0.85	1.73	7.77	4.58	1.52	99.78	
Molecular Numbers	.897	.193	.039	.050	.021	.031	.125	.049	Salic Minerals	Femic Minerals	
294	49							49	or	27.2	
420	125 {	70					70		ab	36.7	
110	55						55		ne	15.6	
38	19					19			an	5.3	
			39	39							mt 9.1
24			4	4	8	12					di { CaO.SiO <sub>2</sub> 1.39 MgO.SiO <sub>2</sub> .800
10			7	7	13						FeO.SiO <sub>2</sub> .53
											ol { 2MgO.SiO <sub>2</sub> .91 2FeO.SiO <sub>2</sub> .71
896									Sal.	34.8	Fem. 13.4
									Fem.	13.4	
									H <sub>2</sub> O	1.52	
									Sum	99.72	

## ANALYSIS M

LUIAUBOSE (LUIAUBITE). Professional Paper 14, p. 302, last section, No. 1  
Kangerdluaarsuk, Greenland

Percentage {	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO <sub>2</sub>	FeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	ZrO <sub>2</sub>	H <sub>2</sub> O	Sum	Femic Minerals
	51.62	15.63	6.06	4.98	Tr.	3.45	10.09	4.19	2.14	2.12	100.61	
Molecular Numbers	.860	.153	.038	.069		.062	.163	.045	.017	Salic Minerals		
17	.....	.....	.....	.....	.....	.....	.....	.....	17	Z	3.1	.....
270	45	.....	.....	.....	.....	.....	.....	45	.....	or	25.0	.....
90	108 {	15	.....	.....	.....	.....	108 {	15	.....	ab	7.9	.....
186	93	.....	.....	.....	.....	.....	93	.....	.....	ne	26.4	.....
152	.....	38	.....	.....	.....	.....	38	.....	.....	.....	.....	.....
17	.....	.....	.....	.....	.....	.....	17	.....	.....	.....	.....	ac 17.6
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	ns 2.1
124	.....	.....	.....	62	0	62	.....	.....	.....	.....	.....	di 15.4 { CaO.SiO <sub>2</sub> 7.19
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	MgO.SiO <sub>2</sub> .00
4	.....	.....	7	.....	0	.....	.....	.....	.....	.....	.....	FeO.SiO <sub>2</sub> 8.18
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.7 { 2MgO.SiO <sub>2</sub> .00
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	2FeO.SiO <sub>2</sub> .71
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	Sal.	62.4	Fem. 35.8
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	Fem.	35.8	
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	H <sub>2</sub> O	2.12	
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	Sum	100.32	

In N we have a case with  $\text{SiO}_2$  still lower than in M. If we attempt to calculate it in the same way as L and M we find that we have run over on  $\text{SiO}_2$  by 21 units, holding out  $\text{Na}_2\text{O}.\text{Al}_2\text{O}_3$ , 45, for albite and nephelite, and making the allotments for apatite, orthoclase, anorthite, magnetite, diopside, and olivine. We have therefore no  $\text{SiO}_2$  with which to make even nephelite with the 45  $\text{Na}_2\text{O}.\text{Al}_2\text{O}_3$  held out in the beginning.

## ANALYSIS N. TENTATIVE

VESUVIUS (LEUCITE-BASANITE). Professional Paper 14, p. 306, No. 2

Lava of 1872, Mount Vesuvius

Percent- age	$\text{SiO}_2$	$\text{Al}_2\text{O}_3$	$\text{Fe}_2\text{O}_3$	$\text{FeO}$	$\text{MgO}$	$\text{CaO}$	$\text{Na}_2\text{O}$	$\text{K}_2\text{O}$	$\text{P}_2\text{O}_5$	$\text{H}_2\text{O}$	Sum	
	47.65	19.28	2.63	6.48	3.40	9.01	2.78	7.47	.50	.24	99.44	
Molecular Numbers	.794	.189	.016	.090	.085	.161	.045	.080	.004	Salic Minerals	Femic Min- erals	
	480	80				12		80	4		ap	
		45					45			or		
										ab		
	128	64				64				ne		
			16	16						an		
	170			40	45	85					mt	
	37			34	40						di	
											ol	
	815											
	794											
	21	$\text{SiO}_2$										

There is not enough  $\text{SiO}_2$  therefore to begin the calculation by making orthoclase. This case is analogous to the situation in L and M where  $\text{Na}_2\text{O}$  is distributed between albite and nephelite. We proceed by holding out all the  $\text{K}_2\text{O}$  and equal  $\text{Al}_2\text{O}_3$  for a certain amount of orthoclase, and a certain amount of leucite ( $\text{K}_2\text{O}.\text{Al}_2\text{O}_3.4\text{SiO}_2$ ), which calls for less  $\text{SiO}_2$  than orthoclase does. These minerals will each use up  $\text{K}_2\text{O}$  and  $\text{Al}_2\text{O}_3$  in the ratio 1:1. The  $\text{Na}_2\text{O}$  is allotted with  $\text{Al}_2\text{O}_3$  and  $\text{SiO}_2$  to nephelite. This is

ANALYSIS N

VESUVIOSE (LEUCITE-BASANITE). Professional Paper 14, p. 306, No. 2

Lava of 1872, Mount Vesuvius

Percent- age {	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	H <sub>2</sub> O	Sum	
	47.65	19.28	2.63	6.48	3.40	9.01	2.78	7.47	.50	.24	99.44	
Molecular Numbers										Salic Minerals		Femic Minerals
	.794	.189	.016	.090	.085	.161	.045	.080	.004			
	144	80 { 24				12			4			ap 1.3
	224	56						80 { 24		or 13.3		
	90	45					45	56		lc 24.4		
	128	64				64				ne 12.8		
			16	16						an 17.8		
	170			40	45	85						mt 3.7
	37			34	40							di 19.6
												ol 6.3
										Sal. 68.3		Fem. 30.9
										Fem. 30.9		
										H <sub>2</sub> O .24		
										Sum 99.44		

much lower in SiO<sub>2</sub> than albite is. Anorthite, magnetite, diopside and olivine are then made. The SiO<sub>2</sub> remaining over is 369. This is given to the K<sub>2</sub>O.Al<sub>2</sub>O<sub>3</sub>, previously set aside, for orthoclase and leucite, by means of the equations where

$$\begin{aligned}
 &x = \text{the number of molecules of orthoclase} \\
 &\text{and } y = \text{the number of molecules of leucite} \\
 &x + y = K_2O \\
 &\text{and } 6x + 4y = SiO_2 \\
 &\text{Here } x + y = 80 \\
 &6x + 4y = 369 \\
 &x = 24 \\
 &\text{and } y = 56.
 \end{aligned}$$

With leucite and nephelite there will be no quartz nor will there be hypersthene. With leucite in the norm there will be no albite.



Analysis O is like N, in which  $K_2O$  goes partly to orthoclase and partly to leucite, but here we make the minor inflexible molecules ilmenite (il), fluorite (ft), sodium chloride (sc), sodium sulphate (ss), and calcite (cc), at the outset. Where Cl occurs in notable amount with  $P_2O_5$  present it is first allotted to apatite (see Analysis I), and the remainder then takes half as many units of  $Na_2O$  for  $2NaCl$  in sodium chloride. One-half the number of units of Cl is the key. Where  $SO_3$  is present it takes an equal amount of  $Na_2O$  for  $Na_2SO_4$  in sodium sulphate. The number of units of  $SO_3$  is the key.  $CO_2$  when present in a rock usually points to a weathered condition in the rock, the mineral then being present as an alteration product. Where  $CO_2$  occurs in a rock and is not a product of alteration, calcite is an original mineral constituent. In Analysis O we allot to 6 units of  $CO_2$  as many units of CaO for calcite (cc),  $CaO.CO_2$ , the ratio between CaO and  $CO_2$  being 1:1.

In the foregoing examples of calculation a shortage of  $SiO_2$  was met by distributing  $Na_2O.Al_2O_3$  between albite and nephelite, after making orthoclase with  $K_2O.Al_2O_3$ ; or the shortage was provided against, after making nephelite, by distributing  $K_2O.Al_2O_3$  between orthoclase and leucite. With  $SiO_2$  too low for either of these alternatives we may allot  $K_2O.Al_2O_3$  to leucite and  $Na_2O.Al_2O_3$  to nephelite, using up in this way a relatively small amount of  $SiO_2$ . This is the procedure in Analysis P, where we make leucite, nephelite, anorthite, diopside, and olivine, only to find that we have run over by 74 units of  $SiO_2$ . In making diopside we used 302  $SiO_2$ . If now we take CaO from diopside, turn the MgO and FeO thus set free into more olivine, and use the lime (with the requisite amount of  $SiO_2$ ) in ackermanite (am),  $3CaO.2SiO_2$ , which by its formula uses up less  $SiO_2$  for the same amount of CaO than diopside does, we can do away with the  $SiO_2$  deficit. When the ratios of CaO :  $SiO_2$  in diopside, 1:2 (or 2:4), and in ackermanite, 6:4, are considered, it at once appears that ackermanite (am), is the mineral lower in  $SiO_2$  for the same amount of CaO. By taking 87 CaO from the diopside

## ANALYSIS P. TENTATIVE

ALBANOSE (LEUCITITE). Professional Paper 14, p. 350, sec. 4, No. 1  
Alban Hills, Italy

Percent- age {	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	H <sub>2</sub> O	Sum	
	45.99	17.12	4.17	5.38	5.30	10.47	2.18	8.97	.37	.45	100.65	-
Molecular Numbers	.767	.168	.026	.075	.133	.187 BaO .189	.035	.095	.005	Salic Min- erals	Femic Min- erals	
				5				5			il	
	380	95						95		lc		
	70	35					35			ne		
	76	38				38				an		
			26	26								mt
	302			38	113	151						di
	13			6	20							ol
	841											
	767											
	74 Deficit in SiO <sub>2</sub> .											

and using with it 58 SiO<sub>2</sub> we make 29 molecules of ackermanite, *i.e.*, 29 (3CaO.2SiO<sub>2</sub>). By recalculating for new diopside and putting in the 29 molecules of ackermanite (am) (calling for 58 SiO<sub>2</sub> with 87 CaO), we find that as the result there is no deficit of SiO<sub>2</sub>. To ascertain just the right amount of ackermanite to be introduced we make use of the simple formula where

$y = 2/5$  of the deficit of SiO<sub>2</sub>

$y$  = the number of ackermanite molecules to be made.

It appears on trial of all such cases that the deficiency in SiO<sub>2</sub> is exactly allowed for when the number of ackermanite molecules made with CaO taken from diopside equals two-fifths of the SiO<sub>2</sub> deficit, and in consequence we take lime away from diopside equal to three times the number of ackermanite molecules. Numerically it is found that for every unit of CaO taken from diopside and used in ackermanite we gain two-thirds of a unit in

silica, though the process involves the making of new olivine which itself uses up silica. So then to make up a deficit of  $74 \text{ SiO}_2$  we need to take  $87 \text{ CaO}$  from diopside,  $87 \text{ CaO} + 58 \text{ SiO}_2$  making 29 molecules of ackermanite..

In P, therefore, we first allot for ilmenite, leucite, nephelite, anorthite, and magnetite. Then, for ackermanite,  $87 \text{ CaO}$  units are taken from diopside previously made, and used with  $58 \text{ SiO}_2$  for ackermanite in accordance with the formula  $3\text{CaO} \cdot 2\text{SiO}_2$ . In looking up the percentage weight of ackermanite (am), in the table on page 217 the unit of calculation is 29, not 87; *i.e.*, it is one-third the molecular proportion of  $\text{CaO}$  in the ackermanite. The 64 units of  $\text{CaO}$  left over from the original diopside assignment are allotted for new diopside, and the  $\text{MgO}$  and  $\text{FeO}$  thus set free go to olivine.

It should be noted that in this analysis after making diopside there is no excess of  $\text{CaO}$  to be set aside for the making of wollastonite (*cf.* Analysis F). In the following example (Q), 95 molecular units of  $\text{CaO}$  are left over after the making of diopside for wollastonite.

The calculation of Analysis Q differs from that of the preceding example, as was noted just above, in that  $\text{CaO}$  in the tentative allotment is found to cover the  $\text{MgO}$  and  $\text{FeO}$  for diopside and to remain over after this in amount equal to 95 units. These are given to wollastonite (wo),  $\text{CaO} \cdot \text{SiO}_2$ . The silica deficit is 78. By turning 93 of the 95  $\text{CaO}$  of the wollastonite into ackermanite (making in such a case 31 molecules of ackermanite calling for  $93 \text{ CaO}$  and  $62 \text{ SiO}_2$ ), we can do away with a deficit of silica equal to 33. If then our silica deficit were not 78 as it is in this analysis but only 33 or less, enough  $\text{CaO}$  set aside for wollastonite could be converted into ackermanite in this manner to do away with the silica deficit. The formula used is, where  $y$  = the silica deficit,  $y$  = as well the number of ackermanite molecules to be made. This alternative is not open to us in this analysis but it is clear how such calculations are to be treated when they arise. In this case, with insufficient molecules of wollastonite to satisfy the





ANALYSIS Q  
COVORE (NEPHELITE-SYENITE). Professional Paper 14, p. 352, No. 2  
Magnet Cove, Ark.

Percentage {	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	H <sub>2</sub> O	Sum		
	38.93	15.41	5.10	4.24	5.57	16.49	5.27	1.78	1.62	.35	5.20	100.57		
Molecular Numbers											Salic Minerals		Femic Minerals	Tentative
	.649	.151	.032	.059	.139	.294	.085	.019	.020	.002				
						6				2			ap .7	
				20					20				il 3.0	
	76	19						19			lc 8.3			
	170	85					85				ne 24.1			
	94	47				47					an 13.1			
			32	32									mt 7.4	
	(292)			(7)	(139)	(146)								di
	(95)				(95)									wo
	180			4	86	90							di 19.6	
													CaO.SiO <sub>2</sub> 10.44	
													MgO.SiO <sub>2</sub> 8.60	
	28			3	53								FeO.SiO <sub>2</sub> .53	
													2MgO.SiO <sub>2</sub> 3.71	
	100					150							2FeO.SiO <sub>2</sub> .30	
													am 14.4	
											Sal. 45.5		Fem. 49.1	
											Fem. 49.1			
											H <sub>2</sub> O 5.20			
											Sum 99.8			

NOTE.—A deficit of 78 SiO<sub>2</sub> results from this tentative assignment.

deficit of  $\text{SiO}_2$  by their conversion into ackermanite, the molecules of both diopside and wollastonite are to be recalculated to make new diopside, new olivine, and ackermanite by the following equations.

Let  $x$  = the molecules of new diopside

$y$  = the molecules of ackermanite

$z$  = the molecules of new olivine.

Then  $2x + 2y + \frac{z}{2}$  = the available  $\text{SiO}_2$

$x + 3y$  = the available  $\text{CaO}$

$x + z$  = the available  $(\text{MgFe})\text{O}$ .

In this calculation the available  $\text{SiO}_2$  is 309, the  $\text{CaO}$  241, and the  $(\text{MgFe})\text{O}$ , 146.

Therefore (1)  $2x + 2y + \frac{z}{2} = 309$

(2)  $x + 3y = 241$

and (3)  $x + z = 146$ .

From (2), multiplying by 2,

$2x + 6y = 482$ ;

(1)  $2x + 2y + \frac{z}{2} = 309$ ;

subtracting,  $4y - \frac{z}{2} = 173$

or  $12y - 1\frac{1}{2}z = 519$ .

Again (2)  $x + 3y = 241$

(3)  $x + z = 146$ ;

subtracting,  $3y - z = 95$

$12y - 1\frac{1}{2}z = 519$

$12y - 4z = 380$

$y = 50$ , ackermanite

$x = 90$ , new diopside

$z = 56$ , new olivine.

With silica still lower than in Analysis Q we make such a calculation as is given in Analysis R. Here, after the assignment for ilmenite, the  $\text{K}_2\text{O}$ , 79 units, is held out with equal  $\text{Al}_2\text{O}_3$ ,  $\text{Na}_2\text{O}$  takes  $\text{Al}_2\text{O}_3$  as far as it is available (17), and  $\text{SiO}_2$  for nephelite. Extra  $\text{Na}_2\text{O}$ , 9, takes  $\text{Fe}_2\text{O}_3$  and  $\text{SiO}_2$  for acmite.  $\text{Fe}_2\text{O}_3$  remaining takes equal  $\text{FeO}$  for magnetite. All the  $\text{CaO}$ , 296 units, is calculated as ackermanite, and  $\text{MgO}$  and  $\text{FeO}$  remaining over

take  $\text{SiO}_2$  for olivine. Silica is left equal to 229 units. This is distributed with the 79  $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3$  held out (ante), between leucite and kaliophilite (kp),  $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ . The equations are

$$x + y = \text{K}_2\text{O}$$

$$4x + 2y = \text{SiO}_2$$

where  $x$  = the number of molecules of leucite

and  $y$  = the number of molecules of kaliophilite.

$$(1) \quad x + y = 79, \text{K}_2\text{O}$$

$$(2) \quad 4x + 2y = 229, \text{SiO}_2.$$

$$\text{From (1)} \quad 2x + 2y = 158$$

$$2x = 71$$

$$x = 35, \text{leucite molecules}$$

$$y = 44, \text{kaliophilite molecules.}$$

Kaliophilite takes only half as much silica to go with a like amount of  $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3$  as leucite would take, and only a third as much as orthoclase. To calculate the percentage weight of kaliophilite we multiply its molecular number by its molecular weight, 316.

#### ANALYSIS R

VENANZOSE (EUKTOLITE). Professional Paper 14, p. 357, last analysis  
San Venanzo, Umbria, Italy

Percent- age	$\text{SiO}_2$	$\text{Al}_2\text{O}_3$	$\text{Fe}_2\text{O}_3$	FeO	MgO	CaO	$\text{Na}_2\text{O}$	$\text{K}_2\text{O}$	$\text{TiO}_2$	$\text{H}_2\text{O}$	Sum
	41.43	9.80	3.28	5.15	13.40	16.62	1.64	7.40	.29	1.11	100.12
Molecular Numbers	.691	.096	.021	.072	.335	.296	.026	.079	.004	Salic Minerals	Femic Minerals
				4					4		il .6
140	79	{ 35 44						79	{ 35 44	lc	15.3
88										kp	13.9
34							17			ne	4.8
36							9				ac 4.2
			12	12							mt 2.8
197						296					am 28.2
195				56	335						ol 29.2
										Sal. 34.0	Fem. 65.0
										Fem. 65.0	
										$\text{H}_2\text{O}$ 1.11	
										Sum 100.11	

It will be noted that the series of analyses from J to R inclusive illustrates a series of alternative methods for dealing with low  $\text{SiO}_2$ . A slight deficit may be adjusted between hypersthene and olivine. By this device we can do away with a silica deficit equal to one-half  $(\text{MgFe})\text{O}$ . A larger deficit may be provided against by making albite with nephelite after having made orthoclase, under the conditions given above. This saving of silica amounts to a little less than four times the  $\text{Na}_2\text{O}$ . A still larger deficiency in  $\text{SiO}_2$  may be provided for by allotting for orthoclase and leucite after making nephelite. Our making nephelite first in this case saves us an amount of  $\text{SiO}_2$  equal to four times the units of  $\text{Na}_2\text{O}$ , and the subsequent distribution saves a little less than two times the amount of  $\text{K}_2\text{O}$ . With silica still lower it is necessary after making leucite and nephelite, thus saving two times the units of  $\text{K}_2\text{O}$  plus four times the  $\text{Na}_2\text{O}$ , to bring in ackermanite, a device which then saves two-thirds of a unit of  $\text{SiO}_2$  for every unit of  $\text{CaO}$  taken from diopside for ackermanite, or one silica on every three converted from wollastonite into ackermanite. With silica lower still it is necessary to expend as little of it as possible, making nephelite and ackermanite and distributing the silica then remaining between leucite and kaliophilite.

In Analysis S which is calculated like Analysis P, the first of the minor inflexible molecules to be made is chromite (cm),  $\text{FeO} \cdot \text{Cr}_2\text{O}_3$ , the ratio between  $\text{FeO}$  and  $\text{Cr}_2\text{O}_3$  being as 1:1. After ilmenite, which follows, we make perovskite (pf),  $\text{CaO} \cdot \text{TiO}_2$ , with  $\text{CaO} : \text{TiO}_2$ , as 1:1. If silica had been present in abundance we should have made titanite instead of perovskite. (Cf. Analysis I.)

With the lowest known ranges of  $\text{SiO}_2$ , in rocks in which aluminous spinel may form,  $\text{Al}_2\text{O}_3$  and  $(\text{MgFe})\text{O}$  being in excess,  $\text{Al}_2\text{O}_3$  left over after making the feldspars, nephelite, or leucite, is corundum.  $\text{MgO}$  and  $\text{FeO}$  uncombined after their allotment to such minerals as magnetite and ilmenite may have to be entered with the femic minerals simply as  $\text{MgO}$  and  $\text{FeO}$ . Their per-

# QUANTITATIVE CLASSIFICATION OF IGNEOUS ROCKS 1

## ANALYSIS 8

SVERIGARE (MELILITE-BASALT). Professional Paper 14, p. 364, sec. 4, No. 1.  
Hohenstoffeln, Hegau, Baden

Percentage {		SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>	H <sub>2</sub> O	Sum		
		35.56	11.25	6.62	6.67	14.68	8.99	3.86	1.75	8.03	2.66	n.d.	100.07		
Molecular Numbers		.593	.110	.041	.093	.367	.160	.062	.019	.100	.018	Salic Minerals		Femic Minerals	
					18						18			cm 4.0	.018 × 224
					75					75				il 11.4	
				41										hm 6.6	
	76	19							19			lc	8.3		
	124	62						62				ne	17.6		
	58	29					29					an	8.1		
							25			25				pf 3.4	
Tentative	(212)				(0)	106									
Tentative	(130)				(0)	(261)									
SiO <sub>2</sub> deficit equals 7	200				0	100	100							di 21.6	{ CaO.SiO <sub>2</sub> 11.60 MgO.SiO <sub>2</sub> 10.00
	133				0	267								ol 18.7	{ FeO.SiO <sub>2</sub> .00 2MgO.SiO <sub>2</sub> 18.69
	4						6							am .6	{ 2FeO.SiO <sub>2</sub> .00
												Sal. 34.0		Fem. 66.3	
												Fem. 66.3			
												H <sub>2</sub> O			
												Sum 100.3			

centage weights are determined by multiplying them by the molecular weights of MgO and FeO. Such a case is illustrated in Analysis T.

## ANALYSIS T

(MAGNETITE-SPINELLITE.) Professional Paper 14, p. 368, last analysis  
Routivaara, Finland

Percent- age {	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>	H <sub>2</sub> O	Sum
	4.08	6.40	33.43	34.58	3.89	.65	.29	.15	14.25	.20	1.32	99.71

Molecular Numbers	.068	.063	.210 note	.480	.097	.011	.005	.002	.176	.001	Salic Minerals	Femic Minerals
				176					176			il 26.8
	12	2						2			or 1.1	
	30	5					5				ab 2.6	
	22	11				11					an 3.1	
		45									C 4.6	
			210	210								mt 48.7
					97							MgO 3.9
				94								FeO 6.8
											Sal. 11.4	Fem. 86.2
											Fem. 86.2	
											H <sub>2</sub> O 1.32	
											98.92	

NOTE.—Cr<sub>2</sub>O<sub>3</sub>, .001, has been added to Fe<sub>2</sub>O<sub>3</sub>.

The student may now find the following summary of the present chapter useful. A slate may be permanently ruled with a knife for purposes of calculation, and the summary together with the formulæ needed for the various operations may be scratched upon it.

(A). The following fixed minor molecules are provided for by the allotment of

(1), Cr<sub>2</sub>O<sub>3</sub> to cm: (2), TiO<sub>2</sub> to il: (3), P<sub>2</sub>O<sub>5</sub> to ap: (4), Cl to sc: (5), SO<sub>3</sub> to ss: (6), S to pr: (7) CO<sub>2</sub> to cc: (8), ZrO<sub>2</sub> to Z.

(B). With abundant silica, SiO<sub>2</sub>, the succeeding allotments are as follows:

- (9),  $K_2O$  to or; and then, (10), to ks;
- (11),  $Na_2O$  to ab; (12), to ac; (13), to ns;
- (14),  $CaO$  to an;
- (15),  $TiO_2$  to tn; (16) to ru;
- (17),  $Al_2O_3$  to C;
- (18),  $Fe_2O_3$  to mt; (19), to hm;
- (20),  $CaO$  to di; (21), to wo;
- (22),  $FeO$  and  $MgO$  to hy;
- (23),  $SiO_2$  to Q.

(C). With insufficient silica the deficit is made good by the following changes in the above straightforward calculations.

- (a), pf replaces tn;
- (b), ol replaces hy, as far as may be necessary, in part or wholly, (see Anal. J.);
- (c), ne replaces ab, as far as may be necessary, in part or wholly, (see Anal. L);
- (d), lc replaces or, as far as may be necessary, in part or wholly, (see Anal. N);
- (e),  $CaO$  in wo is turned into am;
- (f), sufficient  $CaO$  is taken from di and turned into am;  $MgO$  and  $FeO$  set free are calculated as olivine (Analysis P);
- (g), all the  $CaO$ ,  $(MgFe)O$  and available  $SiO_2$  are recalculated as new di, am and ol, (see Anal. Q);
- (h), kp replaces lc, in part or wholly, after am and ol have been made with  $CaO$ ,  $MgO$  and  $FeO$  (Analysis R);
- (i), with silica still insufficient, excess of  $Al_2O_3$  is C, and uncombined  $(MgFe)O$  is regarded as femic minerals, as in Anal. T.

In the calculation of any given analysis many of the above allotments are not called for, but it is important to note that the procedure is invariably in accordance with the above numbering, step by step.

The student in calculating the analyses given in Professional Paper 14 should not expect to agree exactly in all cases with the calculated norms. Where additions as those of small amounts



of BaO and SrO to CaO have not been made, slight discrepancies may result all along the line. Numerically the allotment to such minerals as diopside, hypersthene and olivine may vary by a single unit one way or the other in MgO and FeO. In P. P. 14 ackermanite is calculated as  $4\text{CaO} \cdot 3\text{SiO}_2$ , instead of  $3\text{CaO} \cdot 2\text{SiO}_2$ . The application of the methods of calculation given in the "Quantitative Classification of Igneous Rocks"<sup>1</sup> should however be precise, the end in view being the correct placing of a given rock where it belongs in the scheme of classification. The method of calculating the norm is necessarily arbitrary in order that concordant results may be obtained by all who make use of it. It should be borne in mind, however, that it agrees with the great body of our observations on the occurrence of minerals in the igneous rocks. The work of calculation has therefore a peculiar value for the student, aside from his needs in classifying rocks, for it directs his thought toward the relations obtaining among the phenomena in cooling rock magmas. It brings home to him why it is that we do not have such an occurrence as that of quartz and nephelite together. It points out to him, for instance, the significance of the presence in a rock of such minerals as corundum, aemite, or perovskite rather than titanite, and it does much to make clear to his mind the significance of each of the mineral molecules occurring in the igneous rocks.

<sup>1</sup> A few slight corrections have been noted by the authors in the *Journal of Geology*, xx., 557. These have been incorporated in the present chapter.

**MOLECULAR NUMBERS OF CHEMICAL COMPONENTS  
OF ROCKS**

SILICA, SiO<sub>2</sub>. MOLECULAR WEIGHT, 60

wt. %	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
35	.583	.585	.586	.588	.590	.591	.593	.595	.596	.598
36	.600	.601	.603	.605	.606	.608	.610	.611	.613	.615
37	.616	.618	.620	.621	.623	.625	.626	.628	.630	.631
38	.633	.635	.636	.638	.640	.641	.643	.645	.646	.648
39	.650	.651	.653	.655	.656	.658	.660	.661	.663	.665
40	.666	.668	.670	.671	.673	.675	.676	.678	.680	.681
41	.683	.685	.686	.688	.690	.691	.693	.695	.696	.698
42	.700	.701	.703	.705	.706	.708	.710	.711	.713	.715
43	.716	.718	.720	.721	.723	.725	.726	.728	.730	.731
44	.733	.735	.736	.738	.740	.741	.743	.745	.746	.748
45	.750	.751	.753	.755	.756	.758	.760	.761	.763	.765
46	.766	.768	.770	.771	.773	.775	.776	.778	.780	.781
47	.783	.785	.786	.788	.790	.791	.793	.795	.796	.798
48	.800	.801	.803	.805	.806	.808	.810	.811	.813	.815
49	.816	.818	.820	.821	.823	.825	.826	.828	.830	.831
50	.833	.835	.836	.838	.840	.841	.843	.845	.846	.848
51	.850	.851	.853	.855	.856	.858	.860	.861	.863	.865
52	.866	.868	.870	.871	.873	.875	.876	.878	.880	.881
53	.883	.885	.886	.888	.890	.891	.893	.895	.896	.898
54	.900	.901	.903	.905	.906	.908	.910	.911	.913	.915
55	.916	.918	.920	.921	.923	.925	.926	.928	.930	.931
56	.933	.935	.936	.938	.940	.941	.943	.945	.946	.948
57	.950	.951	.953	.955	.956	.958	.960	.961	.963	.965
58	.966	.968	.970	.971	.973	.975	.976	.978	.980	.981
59	.983	.985	.986	.988	.990	.991	.993	.995	.996	.998
60	1.000	1.001	1.003	1.005	1.006	1.008	1.010	1.011	1.013	1.015
61	1.016	1.018	1.020	1.021	1.023	1.025	1.026	1.028	1.030	1.031
62	1.033	1.035	1.036	1.038	1.040	1.041	1.043	1.045	1.046	1.048
63	1.050	1.051	1.053	1.055	1.056	1.058	1.060	1.061	1.063	1.065
64	1.066	1.068	1.070	1.071	1.073	1.075	1.076	1.078	1.080	1.081
65	1.083	1.085	1.086	1.088	1.090	1.091	1.093	1.095	1.096	1.098
66	1.100	1.101	1.103	1.105	1.106	1.108	1.110	1.111	1.113	1.115
67	1.116	1.118	1.120	1.121	1.123	1.125	1.126	1.128	1.130	1.131
68	1.133	1.135	1.136	1.138	1.140	1.141	1.143	1.145	1.146	1.148
69	1.150	1.151	1.153	1.155	1.156	1.158	1.160	1.161	1.163	1.165
70	1.166	1.168	1.170	1.171	1.173	1.175	1.176	1.178	1.180	1.181
71	1.183	1.185	1.186	1.188	1.190	1.191	1.193	1.195	1.196	1.198
72	1.200	1.201	1.203	1.205	1.206	1.208	1.210	1.211	1.213	1.215
73	1.216	1.218	1.220	1.221	1.223	1.225	1.226	1.228	1.230	1.231
74	1.233	1.235	1.236	1.238	1.240	1.241	1.243	1.245	1.246	1.248
75	1.250	1.251	1.253	1.255	1.256	1.258	1.260	1.261	1.263	1.265
76	1.266	1.268	1.270	1.271	1.273	1.275	1.276	1.278	1.280	1.281
77	1.283	1.285	1.286	1.288	1.290	1.291	1.293	1.295	1.296	1.298

ALUMINA,  $\text{Al}_2\text{O}_3$ . MOLECULAR WEIGHT, 102

%	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	%
0	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	0
1	.010	.011	.012	.013	.014	.015	.016	.017	.018	.019	1
2	.020	.021	.022	.023	.024	.025	.025	.026	.027	.028	2
3	.029	.030	.031	.032	.033	.034	.035	.036	.037	.038	3
4	.039	.040	.041	.042	.043	.044	.045	.046	.047	.048	4
5	.049	.050	.051	.052	.053	.054	.055	.056	.057	.058	5
6	.059	.060	.061	.062	.063	.064	.065	.066	.067	.068	6
7	.069	.070	.071	.072	.073	.074	.075	.075	.076	.077	7
8	.078	.079	.080	.081	.082	.083	.084	.085	.086	.087	8
9	.088	.089	.090	.091	.092	.093	.094	.095	.096	.097	9
10	.098	.099	.100	.101	.102	.103	.104	.105	.106	.107	10
11	.108	.109	.110	.111	.112	.113	.114	.115	.116	.117	11
12	.118	.119	.120	.121	.122	.123	.124	.125	.125	.126	12
13	.127	.128	.129	.130	.131	.132	.133	.134	.135	.136	13
14	.137	.138	.139	.140	.141	.142	.143	.144	.145	.146	14
15	.147	.148	.149	.150	.151	.152	.153	.154	.155	.156	15
16	.157	.158	.159	.160	.161	.162	.163	.164	.165	.166	16
17	.167	.168	.169	.170	.171	.172	.173	.174	.175	.175	17
18	.176	.177	.178	.179	.180	.181	.182	.183	.184	.185	18
19	.186	.187	.188	.189	.190	.191	.192	.193	.194	.195	19
20	.196	.197	.198	.199	.200	.201	.202	.203	.204	.205	20
21	.206	.207	.208	.209	.210	.211	.212	.213	.214	.215	21
22	.216	.217	.218	.219	.220	.221	.222	.223	.224	.225	22
23	.225	.226	.227	.228	.229	.230	.231	.232	.233	.234	23
24	.235	.236	.237	.238	.239	.240	.241	.242	.243	.244	24
25	.245	.246	.247	.248	.249	.250	.251	.252	.253	.254	25
26	.255	.256	.257	.258	.259	.260	.261	.262	.263	.264	26
27	.265	.266	.267	.268	.269	.270	.271	.272	.273	.274	27
28	.275	.275	.276	.277	.278	.279	.280	.281	.282	.283	28
29	.284	.285	.286	.287	.288	.289	.290	.291	.292	.293	29

FERRIC OXIDE,  $\text{Fe}_2\text{O}_3$ . MOLECULAR WEIGHT, 160

%	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	%
0	.000	.001	.001	.002	.003	.003	.004	.004	.005	.006	0
1	.006	.007	.008	.008	.009	.009	.010	.011	.011	.012	1
2	.013	.013	.014	.014	.015	.016	.016	.017	.018	.018	2
3	.019	.019	.020	.021	.021	.022	.023	.023	.024	.024	3
4	.025	.026	.026	.027	.028	.028	.029	.029	.030	.031	4
5	.031	.032	.033	.033	.034	.034	.035	.036	.036	.037	5
6	.038	.038	.039	.039	.040	.041	.041	.042	.043	.043	6
7	.044	.044	.045	.046	.046	.047	.048	.048	.049	.049	7
8	.050	.051	.051	.052	.053	.053	.054	.054	.055	.056	8
9	.056	.057	.058	.058	.059	.059	.060	.061	.061	.062	9
10	.063	.063	.064	.064	.065	.066	.066	.067	.068	.068	10
11	.069	.069	.070	.071	.071	.072	.073	.073	.074	.074	11
12	.075	.076	.076	.077	.078	.078	.079	.079	.080	.081	12
13	.081	.082	.083	.083	.084	.084	.085	.086	.086	.087	13
14	.088	.088	.089	.089	.090	.091	.091	.092	.093	.093	14
15	.094	.094	.095	.096	.096	.097	.098	.098	.099	.099	15
16	.100	.101	.101	.102	.103	.103	.104	.104	.105	.106	16
17	.106	.107	.108	.108	.109	.109	.110	.111	.111	.112	17
18	.113	.113	.114	.114	.115	.116	.116	.117	.118	.118	18
19	.119	.119	.120	.121	.121	.122	.123	.123	.124	.124	19

## FERROUS OXIDE, FeO. MOLECULAR WEIGHT, 72

%	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	%
0	.000	.001	.003	.004	.006	.007	.008	.010	.011	.013	0
1	.014	.015	.017	.018	.019	.021	.022	.024	.025	.026	1
2	.028	.029	.031	.032	.033	.035	.036	.038	.039	.040	2
3	.042	.043	.044	.046	.047	.049	.050	.051	.053	.054	3
4	.056	.057	.058	.060	.061	.063	.064	.065	.067	.068	4
5	.069	.071	.072	.074	.075	.076	.078	.079	.081	.082	5
6	.083	.085	.086	.088	.089	.090	.092	.093	.094	.096	6
7	.097	.099	.100	.101	.103	.104	.106	.107	.108	.110	7
8	.111	.113	.114	.115	.117	.118	.119	.121	.122	.124	8
9	.125	.126	.128	.129	.131	.132	.133	.135	.136	.138	9
10	.139	.140	.142	.143	.144	.146	.147	.149	.150	.151	10
11	.153	.154	.156	.157	.158	.160	.161	.163	.164	.165	11
12	.167	.168	.169	.171	.172	.174	.175	.176	.178	.179	12
13	.181	.182	.183	.185	.186	.188	.189	.190	.192	.193	13
14	.194	.196	.197	.199	.200	.201	.203	.204	.206	.207	14
15	.208	.210	.211	.213	.214	.215	.217	.218	.219	.221	15
16	.222	.224	.225	.226	.228	.229	.231	.232	.233	.235	16
17	.236	.238	.239	.240	.242	.243	.244	.246	.247	.249	17
18	.250	.251	.253	.254	.256	.257	.258	.260	.261	.263	18
19	.264	.265	.267	.268	.269	.271	.272	.274	.275	.276	19

**Magnesia, MgO. Molecular Weight, 40**

Divide Percentage Weight by 40

**LIME, CaO. MOLECULAR WEIGHT, 56**

%	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	%
0	.000	.002	.004	.005	.007	.009	.011	.013	.014	.016	0
1	.018	.020	.021	.023	.025	.027	.029	.030	.032	.034	1
2	.036	.038	.039	.041	.043	.045	.046	.048	.050	.052	2
3	.054	.055	.057	.059	.061	.063	.064	.066	.068	.070	3
4	.071	.073	.075	.077	.079	.080	.082	.084	.086	.088	4
5	.089	.091	.093	.095	.096	.098	.100	.102	.104	.105	5
6	.107	.109	.111	.113	.114	.116	.118	.120	.121	.123	6
7	.125	.127	.129	.130	.132	.134	.136	.138	.139	.141	7
8	.143	.145	.146	.148	.150	.152	.154	.155	.157	.159	8
9	.161	.163	.164	.166	.168	.170	.171	.173	.175	.177	9
10	.179	.180	.182	.184	.186	.188	.189	.191	.193	.195	10
11	.196	.198	.200	.202	.204	.205	.207	.209	.211	.213	11
12	.214	.216	.218	.220	.221	.223	.225	.227	.229	.230	12
13	.232	.234	.236	.238	.239	.241	.243	.245	.246	.248	13
14	.250	.252	.254	.255	.257	.259	.261	.263	.264	.266	14
15	.268	.270	.271	.273	.275	.277	.279	.280	.282	.284	15
16	.286	.288	.289	.291	.293	.295	.296	.298	.300	.302	16
17	.304	.305	.307	.309	.311	.313	.314	.316	.318	.320	17
18	.321	.323	.325	.327	.329	.330	.332	.334	.336	.338	18
19	.339	.341	.343	.345	.346	.348	.350	.352	.354	.355	19
20	.357	.358	.360	.362	.364	.366	.367	.369	.371	.373	20
21	.375	.376	.378	.380	.382	.383	.385	.387	.389	.391	21
22	.392	.394	.396	.398	.400	.401	.403	.405	.407	.408	22
23	.410	.412	.414	.416	.417	.419	.421	.423	.425	.426	23
24	.428	.430	.432	.433	.435	.437	.439	.441	.442	.444	24

SODA, Na<sub>2</sub>O. MOLECULAR WEIGHT, 62

%	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	%
0	.000	.002	.003	.005	.006	.008	.010	.011	.013	.015	0
1	.016	.018	.019	.021	.023	.024	.026	.027	.029	.031	1
2	.032	.034	.035	.037	.039	.040	.042	.044	.045	.047	2
3	.048	.050	.052	.053	.055	.056	.058	.060	.061	.063	3
4	.065	.066	.068	.069	.071	.073	.074	.076	.077	.079	4
5	.081	.082	.084	.085	.087	.089	.090	.092	.094	.095	5
6	.097	.098	.100	.102	.103	.105	.106	.108	.110	.111	6
7	.113	.115	.116	.118	.119	.121	.123	.124	.126	.127	7
8	.129	.131	.132	.134	.135	.137	.139	.140	.142	.144	8
9	.145	.147	.148	.150	.152	.153	.155	.156	.158	.160	9
10	.161	.163	.165	.166	.168	.169	.171	.173	.174	.176	10
11	.177	.179	.181	.182	.184	.185	.187	.189	.190	.192	11
12	.194	.195	.197	.198	.200	.202	.203	.205	.206	.208	12
13	.210	.211	.213	.215	.216	.218	.219	.221	.223	.224	13
14	.226	.227	.229	.231	.232	.234	.235	.237	.239	.240	14
15	.242	.244	.245	.247	.248	.250	.252	.253	.255	.256	15
16	.258	.260	.261	.263	.265	.266	.268	.269	.271	.273	16
17	.274	.276	.277	.279	.281	.282	.284	.285	.287	.289	17
18	.290	.292	.294	.295	.297	.298	.300	.302	.303	.305	18
19	.306	.308	.310	.311	.313	.315	.316	.318	.319	.321	19



POTASH, K<sub>2</sub>O. MOLECULAR WEIGHT, 94

%	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	%
0	.000	.001	.002	.003	.004	.005	.006	.007	.009	.010	0
1	.011	.012	.013	.014	.015	.016	.017	.018	.019	.020	1
2	.021	.022	.023	.024	.026	.027	.028	.029	.030	.031	2
3	.032	.033	.034	.035	.036	.037	.038	.039	.040	.041	3
4	.042	.044	.045	.046	.047	.048	.049	.050	.051	.052	4
5	.053	.054	.055	.056	.057	.059	.060	.061	.062	.063	5
6	.064	.065	.066	.067	.068	.069	.070	.071	.072	.073	6
7	.074	.076	.077	.078	.079	.080	.081	.082	.083	.084	7
8	.085	.086	.087	.088	.089	.090	.091	.093	.094	.095	8
9	.096	.097	.098	.099	.100	.101	.102	.103	.104	.105	9
10	.106	.107	.109	.110	.111	.112	.113	.114	.115	.116	10
11	.117	.118	.119	.120	.121	.122	.123	.124	.126	.127	11
12	.128	.129	.130	.131	.132	.133	.134	.135	.136	.137	12
13	.138	.139	.140	.141	.143	.144	.145	.146	.147	.148	13
14	.149	.150	.151	.152	.153	.154	.155	.156	.157	.159	14
15	.160	.161	.162	.163	.164	.165	.166	.167	.168	.169	15
16	.170	.171	.172	.173	.174	.176	.177	.178	.179	.180	16
17	.181	.182	.183	.184	.185	.186	.187	.188	.189	.190	17
18	.191	.193	.194	.195	.196	.197	.198	.199	.200	.201	18
19	.202	.203	.204	.205	.206	.207	.209	.210	.211	.212	19

TITANIC ACID,  $\text{TiO}_2$ . MOLECULAR WEIGHT, 80

%	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	%
0	.000	.001	.003	.004	.005	.006	.008	.009	.010	.011	0
1	.013	.014	.015	.016	.018	.019	.020	.021	.023	.024	1
2	.025	.026	.028	.029	.030	.031	.033	.034	.035	.036	2
3	.038	.039	.040	.041	.043	.044	.045	.046	.048	.049	3
4	.050	.051	.053	.054	.055	.056	.058	.059	.060	.061	4
5	.063	.064	.065	.066	.068	.069	.070	.071	.073	.074	5
6	.075	.076	.078	.079	.080	.081	.083	.084	.085	.086	6
7	.088	.089	.090	.091	.093	.094	.095	.096	.098	.099	7
8	.100	.101	.103	.104	.105	.106	.108	.109	.110	.111	8
9	.113	.114	.115	.116	.118	.119	.120	.121	.123	.124	9

PHOSPHORIC PENTOXIDE,  $\text{P}_2\text{O}_5$ . MOLECULAR WEIGHT, 142

%	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	%
0	.000	.001	.001	.002	.003	.004	.004	.005	.006	.006	0
1	.007	.008	.008	.009	.010	.011	.011	.012	.013	.013	1
2	.014	.015	.015	.016	.017	.018	.018	.019	.020	.020	2
3	.021	.022	.023	.023	.024	.025	.025	.026	.027	.027	3
4	.028	.029	.030	.030	.031	.032	.032	.033	.034	.035	4
5	.035	.036	.037	.037	.038	.039	.039	.040	.041	.042	5

ZIRCONIA,  $\text{ZrO}_2$ . MOLECULAR WEIGHT, 123

%	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	%
0	.000	.001	.002	.002	.003	.004	.005	.006	.007	.007	0
1	.008	.009	.010	.011	.011	.012	.013	.014	.015	.015	1
2	.016	.017	.018	.019	.020	.020	.021	.022	.023	.024	2
3	.024	.025	.026	.027	.028	.028	.029	.030	.031	.032	3
4	.033	.033	.034	.035	.036	.037	.037	.038	.039	.040	4
5	.041	.042	.042	.043	.044	.045	.046	.046	.047	.048	5

CARBONIC ACID, CO<sub>2</sub>. MOLECULAR WEIGHT, 44

%	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	%
0	.000	.002	.005	.007	.009	.011	.014	.016	.018	.020	0
1	.023	.025	.027	.030	.032	.034	.036	.039	.041	.043	1
2	.045	.048	.050	.052	.055	.057	.059	.061	.064	.066	2
3	.068	.070	.073	.075	.077	.080	.082	.084	.086	.089	3
4	.091	.093	.095	.098	.100	.102	.105	.107	.109	.111	4
5	.114	.116	.118	.120	.123	.125	.127	.130	.132	.134	5
6	.136	.139	.141	.143	.145	.148	.150	.152	.155	.157	6
7	.159	.161	.164	.166	.168	.170	.173	.175	.177	.180	7
8	.182	.184	.186	.189	.191	.193	.195	.198	.200	.202	8
9	.205	.207	.209	.211	.214	.216	.218	.220	.223	.225	9

SULPHURIC ANHYDRIDE, SO<sub>3</sub>. MOLECULAR WEIGHT, 80

%	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	%
0	.000	.001	.003	.004	.005	.006	.008	.009	.010	.011	0
1	.013	.014	.015	.016	.018	.019	.020	.021	.023	.024	1
2	.025	.026	.028	.029	.030	.031	.033	.034	.035	.036	2
3	.038	.039	.040	.041	.043	.044	.045	.046	.048	.049	3
4	.050	.051	.053	.054	.055	.056	.058	.059	.060	.061	4

## CHLORINE, Cl. ATOMIC WEIGHT, 35.5

%	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	%
0	.000	.003	.006	.009	.011	.014	.017	.020	.023	.025	0
1	.028	.031	.034	.037	.039	.042	.045	.048	.051	.054	1
2	.056	.059	.062	.065	.068	.070	.073	.076	.079	.082	2
3	.085	.087	.090	.093	.096	.099	.101	.104	.107	.110	3

MANGANOUS OXIDE, MnO. MOLECULAR WEIGHT, 71

%	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	%
0	.000	.001	.003	.004	.006	.007	.008	.010	.011	.013	0
1	.014	.015	.017	.018	.020	.021	.023	.024	.025	.027	1
2	.028	.030	.031	.032	.034	.035	.037	.038	.039	.041	2
3	.042	.044	.045	.046	.048	.049	.051	.052	.054	.055	3

FLUORINE, F. MOLECULAR WEIGHT, 19

%	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	%
0	.000	.005	.011	.016	.021	.026	.032	.037	.042	.047	0
1	.053	.058	.063	.068	.074	.079	.084	.089	.095	.100	1

BARYTA, BaO. MOLECULAR WEIGHT, 153.5

%	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	%
0	.000	.001	.001	.002	.003	.003	.004	.005	.005	.006	0
1	.007	.007	.008	.009	.009	.010	.010	.011	.012	.012	1
2	.013	.014	.014	.015	.016	.016	.017	.018	.018	.019	2
3	.020	.020	.021	.022	.022	.023	.024	.024	.025	.026	3

STRONTIA, SrO. MOLECULAR WEIGHT, 103.5

%	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	%
0	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	0
1	.010	.011	.012	.013	.014	.014	.015	.016	.017	.018	1

**PERCENTAGE WEIGHTS FOR VARIOUS PROPORTIONS OF  
MOLECULES OF THE STANDARD ROCK-  
MAKING MINERALS**

**Quartz,  $\text{SiO}_2$ , Molecular Weight, 60**

Multiply the molecular number of  $\text{SiO}_2$  by 60

**ORTHOCLASE,  $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$ . MOLECULAR WEIGHT,  
556**

Mol. wt.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.56	1.11	1.67	2.22	2.78	3.34	3.89	4.45	5.00	.00
.01	5.56	6.12	6.67	7.23	7.78	8.34	8.90	9.45	10.01	10.56	.01
.02	11.12	11.68	12.23	12.79	13.34	13.90	14.46	15.01	15.57	16.12	.02
.03	16.68	17.24	17.79	18.35	18.90	19.46	20.02	20.57	21.13	21.68	.03
.04	22.24	22.80	23.35	23.91	24.46	25.02	25.58	26.13	26.69	27.24	.04
.05	27.80	28.36	28.91	29.47	30.02	30.58	31.14	31.69	32.25	32.80	.05
.06	33.36	33.92	34.47	35.03	35.58	36.14	36.70	37.25	37.81	38.36	.06
.07	38.92	39.48	40.03	40.59	41.14	41.70	42.26	42.81	43.37	43.92	.07
.08	44.48	45.04	45.59	46.15	46.70	47.26	47.82	48.37	48.93	49.48	.08
.09	50.04	50.60	51.15	51.71	52.26	52.82	53.38	53.93	54.49	55.04	.09
.10	55.60	56.16	56.71	57.27	57.82	58.38	58.94	59.49	60.05	60.60	.10
.11	61.16	61.72	62.27	62.83	63.38	63.94	64.50	65.05	65.61	66.16	.11
.12	66.72	67.28	67.83	68.39	68.94	69.50	70.06	70.61	71.17	71.72	.12
.13	72.28	72.84	73.39	73.95	74.50	75.06	75.62	76.17	76.73	77.28	.13
.14	77.84	78.40	78.95	79.51	80.06	80.62	81.18	81.73	82.29	82.84	.14
.15	83.40	83.96	84.51	85.07	85.62	86.18	86.74	87.30	87.85	88.40	.15
.16	88.96	89.52	90.07	90.63	91.18	91.74	92.30	92.85	93.41	93.96	.16
.17	94.52	95.08	95.63	96.19	96.74	97.30	97.85	98.41	98.97	99.52	.17
.18	100.08	.....	.....	.....	.....	.....	.....	.....	.....	.....	.18

ALBITE,  $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$ . MOLECULAR WEIGHT, 524

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.52	1.05	1.57	2.10	2.62	3.14	3.67	4.19	4.72	.00
.01	5.24	5.76	6.29	6.81	7.34	7.86	8.38	8.91	9.43	9.96	.01
.02	10.48	11.00	11.53	12.05	12.58	13.10	13.62	14.15	14.67	15.20	.02
.03	15.72	16.24	16.77	17.29	17.82	18.34	18.86	19.39	19.91	20.44	.03
.04	20.96	21.48	22.01	22.53	23.06	23.58	24.10	24.63	25.15	25.68	.04
.05	26.20	26.72	27.25	27.77	28.30	28.82	29.34	29.87	30.39	30.92	.05
.06	31.44	31.96	32.49	33.01	33.54	34.06	34.58	35.11	35.63	36.15	.06
.07	36.68	37.20	37.73	38.25	38.77	39.30	39.82	40.35	40.87	41.39	.07
.08	41.92	42.44	42.97	43.49	44.01	44.54	45.06	45.59	46.11	46.63	.08
.09	47.16	47.68	48.21	48.73	49.25	49.78	50.30	50.83	51.35	51.87	.09
.10	52.40	52.92	53.45	53.97	54.49	55.02	55.54	56.07	56.59	57.11	.10
.11	57.64	58.16	58.69	59.21	59.73	60.26	60.78	61.31	61.83	62.35	.11
.12	62.88	63.40	63.93	64.45	64.97	65.50	66.02	66.55	67.07	67.59	.12
.13	68.12	68.64	69.17	69.69	70.21	70.74	71.26	71.79	72.31	72.83	.13
.14	73.36	73.88	74.41	74.93	75.45	75.98	76.50	77.03	77.55	78.07	.14
.15	78.60	79.12	79.65	80.17	80.70	81.22	81.72	82.28	82.79	83.32	.15
.16	83.84	84.36	84.89	85.41	85.94	86.46	86.98	87.51	88.03	88.56	.16
.17	89.08	89.60	90.13	90.65	91.18	91.70	92.22	92.75	93.27	93.80	.17
.18	94.32	94.84	95.37	95.89	96.42	96.94	97.46	97.99	98.51	99.04	.18
.19	99.56	100.08	.....	.....	.....	.....	.....	.....	.....	.....	.19

ANORTHITE,  $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ . MOLECULAR WEIGHT,  
278

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.28	.56	.83	1.11	1.39	1.67	1.95	2.22	2.50	.00
.01	2.78	3.06	3.34	3.61	3.89	4.17	4.45	4.73	5.00	5.28	.01
.02	5.56	5.84	6.12	6.39	6.67	6.95	7.23	7.51	7.78	8.06	.02
.03	8.34	8.62	8.90	9.17	9.45	9.73	10.01	10.29	10.56	10.84	.03
.04	11.12	11.40	11.68	11.95	12.23	12.51	12.79	13.07	13.34	13.62	.04
.05	13.90	14.18	14.46	14.73	15.01	15.29	15.57	15.85	16.12	16.40	.05
.06	16.68	16.96	17.24	17.51	17.79	18.07	18.35	18.63	18.90	19.18	.06
.07	19.46	19.74	20.02	20.29	20.57	20.85	21.13	21.41	21.68	21.96	.07
.08	22.24	22.52	22.80	23.07	23.35	23.63	23.91	24.19	24.46	24.74	.08
.09	25.02	25.30	25.58	25.85	26.13	26.41	26.69	26.97	27.24	27.52	.09
.10	27.80	28.08	28.36	28.63	28.91	29.19	29.47	29.75	30.02	30.30	.10
.11	30.58	30.86	31.14	31.41	31.69	31.97	32.25	32.53	32.80	33.08	.11
.12	33.36	33.64	33.92	34.19	34.47	34.75	35.03	35.31	35.58	35.86	.12
.13	36.14	36.42	36.70	36.97	37.25	37.53	37.81	38.09	38.36	38.64	.13
.14	38.92	39.20	39.48	39.75	40.03	40.31	40.59	40.87	41.14	41.42	.14
.15	41.70	41.98	42.26	42.53	42.81	43.09	43.37	43.65	43.92	44.20	.15
.16	44.48	44.76	45.04	45.31	45.59	45.87	46.15	46.43	46.70	46.98	.16
.17	47.26	47.54	47.82	48.09	48.37	48.65	48.93	49.21	49.48	49.76	.17
.18	50.04	50.32	50.60	50.87	51.15	51.43	51.71	51.99	52.26	52.54	.18
.19	52.82	53.10	53.38	53.65	53.93	54.21	54.49	54.77	55.04	55.32	.19
.20	55.60	55.88	56.16	56.43	56.71	56.99	57.27	57.55	57.82	58.10	.20
.21	58.38	58.66	58.94	59.21	59.49	59.77	60.05	60.33	60.60	60.88	.21
.22	61.16	61.44	61.72	61.99	62.27	62.55	62.83	63.11	63.38	63.66	.22
.23	63.94	64.22	64.50	64.77	65.05	65.33	65.61	65.89	66.16	66.44	.23
.24	66.72	67.00	67.28	67.55	67.83	68.11	68.39	68.67	68.94	69.22	.24

NEPHELITE,  $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ . MOLECULAR WEIGHT,  
284

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.28	.57	.85	1.14	1.42	1.70	1.99	2.27	2.56	.00
.01	2.84	3.12	3.41	3.69	3.98	4.26	4.54	4.83	5.11	5.40	.01
.02	5.68	5.94	6.25	6.53	6.82	7.10	7.38	7.67	7.95	8.24	.02
.03	8.52	8.80	9.09	9.37	9.66	9.94	10.22	10.51	10.79	11.08	.03
.04	11.36	11.64	11.93	12.21	12.50	12.78	13.06	13.35	13.63	13.92	.04
.05	14.20	14.48	14.77	15.05	15.34	15.62	15.90	16.19	16.47	16.76	.05
.06	17.04	17.32	17.61	17.89	18.18	18.46	18.74	19.03	19.31	19.60	.06
.07	19.88	20.16	20.45	20.73	21.02	21.30	21.58	21.87	22.15	22.44	.07
.08	22.72	23.00	23.28	23.57	23.86	24.14	24.42	24.71	24.99	25.28	.08
.09	25.56	25.84	26.13	26.41	26.70	26.98	27.26	27.55	27.83	28.12	.09
.10	28.40	28.68	28.97	29.25	29.54	29.82	30.10	30.39	30.67	30.96	.10
.11	31.24	31.52	31.81	32.09	32.38	32.66	32.94	33.23	33.51	33.80	.11
.12	34.08	34.36	34.65	34.93	35.22	35.50	35.78	36.07	36.35	36.64	.12
.13	36.92	37.20	37.49	37.77	38.06	38.34	38.62	38.91	39.19	39.48	.13
.14	39.76	40.04	40.33	40.61	40.90	41.18	41.46	41.75	41.93	42.32	.14
.15	42.60	42.88	43.17	43.45	43.74	44.02	44.30	44.59	44.87	45.16	.15
.16	45.44	45.72	46.01	46.29	46.58	46.86	47.14	47.43	47.71	48.00	.16
.17	48.28	48.56	48.85	49.13	49.42	49.70	49.98	50.27	50.55	50.84	.17
.18	51.12	51.40	51.69	51.97	52.26	52.54	52.82	53.11	53.39	53.68	.18
.19	53.96	54.24	54.53	54.81	55.10	55.38	55.66	55.95	56.23	56.52	.19



LEUCITE,  $K_2O \cdot Al_2O_3 \cdot 4SiO_2$ . MOLECULAR WEIGHT, 436

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.44	.87	1.31	1.74	2.18	2.62	3.05	3.49	3.92	.00
.01	4.36	4.80	5.23	5.67	6.10	6.54	6.98	7.41	7.85	8.28	.01
.02	8.72	9.16	9.59	10.03	10.46	10.90	11.34	11.77	12.21	12.64	.02
.03	13.08	13.52	13.95	14.39	14.82	15.26	15.70	16.13	16.57	17.00	.03
.04	17.44	17.88	18.31	18.75	19.18	19.62	20.06	20.49	20.93	21.36	.04
.05	21.80	22.24	22.67	23.11	23.54	23.98	24.42	24.85	25.29	25.72	.05
.06	26.16	26.60	27.03	27.47	27.90	28.34	28.78	29.21	29.65	30.08	.06
.07	30.52	30.96	31.39	31.83	32.26	32.70	33.14	33.57	34.01	34.44	.07
.08	34.88	35.32	35.75	36.19	36.62	37.06	37.50	37.93	38.37	38.80	.08
.09	39.24	39.68	40.11	40.55	40.98	41.42	41.86	42.29	42.73	43.16	.09
.10	43.60	44.04	44.47	44.91	45.34	45.78	46.22	46.65	47.09	47.52	.10
.11	47.96	48.40	48.83	49.27	49.70	50.14	50.58	51.01	51.45	51.88	.11
.12	52.32	52.76	53.19	53.63	54.06	54.50	54.94	55.37	55.81	56.24	.12
.13	56.68	57.12	57.55	57.99	58.42	58.86	59.30	59.73	60.17	60.60	.13
.14	61.04	61.48	61.91	62.35	62.78	63.22	63.66	64.09	64.53	64.96	.14

SODIUM CHLORIDE,  $Na_2Cl_2$ . MOLECULAR WEIGHT, 117

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.12	.23	.35	.47	.59	.70	.82	.94	1.05	.00
.01	1.17	1.29	1.40	1.52	1.64	1.76	1.87	1.99	2.11	2.22	.01
.02	2.34	2.46	2.57	2.69	2.81	2.93	3.04	3.16	3.28	3.39	.02
.03	3.51	3.63	3.74	3.86	3.98	4.10	4.21	4.33	4.45	4.56	.03
.04	4.68	4.80	4.91	5.03	5.15	5.27	5.38	5.50	5.62	5.73	.04

SODIUM SULPHATE,  $\text{Na}_2\text{SO}_4$ . MOLECULAR WEIGHT, 142

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.14	.28	.43	.57	.71	.85	.99	1.14	1.28	.00
.01	1.42	1.56	1.70	1.85	1.99	2.13	2.27	2.41	2.56	2.70	.01
.02	2.84	2.98	3.12	3.27	3.41	3.55	3.69	3.83	3.98	4.12	.02
.03	4.26	4.40	4.54	4.69	4.83	4.97	5.11	5.25	5.40	5.54	.03
.04	5.68	5.82	5.96	6.11	6.25	6.39	6.53	6.67	6.82	6.96	.04

CORUNDUM,  $\text{Al}_2\text{O}_3$ . MOLECULAR WEIGHT, 102

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.10	.20	.31	.41	.51	.61	.71	.82	.92	.00
.01	1.02	1.12	1.22	1.33	1.43	1.53	1.63	1.73	1.84	1.94	.01
.02	2.04	2.14	2.24	2.35	2.45	2.55	2.65	2.75	2.86	2.96	.02
.03	3.06	3.16	3.26	3.37	3.47	3.57	3.67	3.77	3.88	3.98	.03
.04	4.08	4.18	4.28	4.39	4.49	4.59	4.69	4.79	4.90	5.00	.04
.05	5.10	5.20	5.30	5.41	5.51	5.61	5.71	5.81	5.92	6.02	.05
.06	6.12	6.22	6.32	6.43	6.53	6.63	6.73	6.83	6.94	7.04	.06
.07	7.14	7.24	7.34	7.45	7.55	7.65	7.75	7.85	7.96	8.06	.07
.08	8.16	8.26	8.36	8.47	8.57	8.67	8.77	8.87	8.98	9.08	.08
.09	9.18	9.28	9.38	9.49	9.59	9.69	9.76	9.89	10.00	10.10	.09

ZIRCON,  $\text{ZrO}_2\cdot\text{SiO}_2$ . MOLECULAR WEIGHT, 183

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.18	.37	.55	.73	.91	1.10	1.28	1.46	1.65	.00
.01	1.83	2.01	2.20	2.38	2.56	2.75	2.93	3.11	3.29	3.48	.01
.02	3.66	3.84	4.03	4.21	4.39	4.58	4.76	4.94	5.12	5.31	.02
.03	5.49	5.67	5.86	6.04	6.22	6.41	6.59	6.77	6.95	7.14	.03
.04	7.32	7.50	7.78	7.87	8.05	8.24	8.42	8.60	8.78	8.97	.04

CALCIUM METASILICATE (WOLLASTONITE),  $\text{CaO} \cdot \text{SiO}_2$ .  
MOLECULAR WEIGHT, 116

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.12	.23	.35	.46	.58	.70	.81	.93	1.04	.00
.01	1.16	1.28	1.39	1.51	1.63	1.74	1.86	1.97	2.09	2.20	.01
.02	2.32	2.44	2.55	2.67	2.78	2.90	3.02	3.13	3.25	3.36	.02
.03	3.48	3.60	3.71	3.83	3.94	4.06	4.18	4.29	4.41	4.52	.03
.04	4.64	4.76	4.87	4.99	5.10	5.22	5.34	5.45	5.57	5.68	.04
.05	5.80	5.92	6.03	6.15	6.26	6.38	6.50	6.61	6.73	6.84	.05
.06	6.96	7.08	7.19	7.31	7.42	7.54	7.66	7.77	7.89	8.00	.06
.07	8.12	8.24	8.35	8.47	8.58	8.70	8.82	8.93	9.05	9.16	.07
.08	9.28	9.40	9.51	9.63	9.74	9.86	9.98	10.09	10.21	10.32	.08
.09	10.44	10.56	10.67	10.79	10.90	11.02	11.14	11.25	11.37	11.48	.09
.10	11.60	11.72	11.83	11.95	12.06	12.18	12.30	12.41	12.53	12.64	.10
.11	12.76	12.88	12.99	13.11	13.22	13.34	13.46	13.57	13.69	13.80	.11
.12	13.92	14.04	14.15	14.27	14.38	14.50	14.62	14.73	14.85	14.96	.12
.13	15.08	15.20	15.31	15.43	15.54	15.66	15.78	15.89	16.01	16.12	.13
.14	16.24	16.36	16.47	16.59	16.70	16.82	16.93	17.05	17.17	17.28	.14
.15	17.40	17.52	17.63	17.75	17.86	17.98	18.10	18.21	18.33	18.44	.15
.16	18.56	18.68	18.79	18.91	19.02	19.14	19.26	19.37	19.49	19.60	.16
.17	19.72	19.84	19.95	20.07	20.18	20.30	20.42	20.53	20.65	20.76	.17
.18	20.88	21.00	21.11	21.23	21.34	21.46	21.58	21.69	21.81	21.92	.18
.19	22.04	22.16	22.27	22.39	22.50	22.62	22.74	22.85	22.97	23.08	.19

CALCIUM METASILICATE (WOLLASTONITE),  $\text{CaO} \cdot \text{SiO}_2$ .  
 MOLECULAR WEIGHT, 116—(Continued)

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.20	23.20	23.32	23.43	23.55	23.66	23.78	23.90	24.01	24.13	24.24	.20
.21	24.36	24.48	24.59	24.71	24.82	24.94	25.06	25.17	25.29	25.40	.21
.22	25.52	25.64	25.75	25.87	25.98	26.10	26.22	26.33	26.45	26.56	.22
.23	26.68	26.80	26.91	27.03	27.14	27.26	27.38	27.49	27.61	27.72	.23
.24	27.84	27.96	28.07	28.19	28.30	28.42	28.54	28.65	28.77	28.88	.24
.25	29.00	29.12	29.23	29.35	29.46	29.58	29.70	29.81	29.93	30.04	.25
.26	30.16	30.28	30.39	30.51	30.63	30.74	30.86	30.97	31.09	31.20	.26
.27	31.32	31.44	31.55	31.67	31.78	31.90	32.02	32.13	32.25	32.36	.27
.28	32.48	32.60	32.71	32.83	32.94	33.06	33.18	33.29	33.41	33.52	.28
.29	33.64	33.76	33.87	33.99	34.10	34.22	34.34	34.45	34.57	34.68	.29
.30	34.80	34.92	35.03	35.15	35.26	35.38	35.50	35.61	35.73	35.84	.30
.31	35.96	36.08	36.19	36.31	36.42	36.54	36.66	36.77	36.89	37.00	.31
.32	37.12	37.24	37.35	37.47	37.58	37.70	37.82	37.93	38.05	38.16	.32
.33	38.28	38.40	38.51	38.63	38.74	38.86	38.98	39.09	39.21	39.32	.33
.34	39.44	39.56	39.67	39.79	39.90	40.02	40.14	40.25	40.37	40.48	.34
.35	40.60	40.72	40.83	40.95	41.06	41.18	41.30	41.41	41.53	41.64	.35
.36	41.76	41.88	41.99	42.11	42.22	42.34	42.46	42.57	42.69	42.80	.36
.37	42.92	43.04	43.15	43.27	43.38	43.50	43.62	43.73	43.85	43.96	.37
.38	44.08	44.20	44.31	44.43	44.54	44.66	44.78	44.89	45.01	45.12	.38
.39	45.24	45.36	45.47	45.59	45.70	45.82	45.93	46.05	46.17	46.28	.39

**Magnesium Metasilicate  $\text{MgO} \cdot \text{SiO}_2$ . Molecular Weight, 100**

Multiply molecular number by 100

**IRON METASILICATE,  $\text{FeO} \cdot \text{SiO}_2$ . MOLECULAR WEIGHT, 132**

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.13	.26	.40	.53	.66	.79	.92	1.06	1.19	.00
.01	1.32	1.45	1.58	1.72	1.85	1.98	2.11	2.24	2.38	2.51	.01
.02	2.64	2.77	2.90	3.04	3.17	3.30	3.43	3.56	3.70	3.83	.02
.03	3.96	4.09	4.22	4.36	4.49	4.62	4.75	4.88	5.02	5.15	.03
.04	5.28	5.41	5.54	5.68	5.81	5.94	6.07	6.20	6.34	6.47	.04
.05	6.60	6.73	6.86	7.00	7.13	7.26	7.39	7.52	7.66	7.79	.05
.06	7.92	8.05	8.18	8.32	8.45	8.58	8.71	8.84	8.98	9.11	.06
.07	9.24	9.37	9.50	9.64	9.77	9.90	10.03	10.16	10.30	10.43	.07
.08	10.56	10.69	10.82	10.96	11.09	11.22	11.35	11.48	11.62	11.75	.08
.09	11.88	12.01	12.14	12.28	12.41	12.54	12.67	12.80	12.94	13.07	.09
.10	13.20	13.33	13.46	13.60	13.73	13.86	13.99	14.12	14.26	14.39	.10
.11	14.52	14.65	14.78	14.92	15.05	15.18	15.31	15.44	15.58	15.71	.11
.12	15.84	15.97	16.10	16.24	16.37	16.50	16.63	16.76	16.90	17.03	.12
.13	17.16	17.29	17.42	17.56	17.69	17.82	17.95	18.08	18.22	18.35	.13
.14	18.48	18.61	18.74	18.88	19.01	19.14	19.27	19.40	19.54	19.67	.14
.15	19.80	19.93	20.06	20.20	20.33	20.46	20.59	20.72	20.86	20.99	.15
.16	21.12	21.25	21.38	21.52	21.65	21.78	21.91	22.04	22.18	22.31	.16
.17	22.44	22.57	22.70	22.84	22.97	23.10	23.23	23.36	23.50	23.63	.17
.18	23.76	23.89	24.02	24.16	24.29	24.42	24.55	24.68	24.82	24.95	.18
.19	25.08	25.21	25.34	25.48	25.61	25.74	25.87	26.00	26.14	26.27	.19

IRON METASILICATE,  $\text{FeO} \cdot \text{SiO}_2$ . MOLECULAR  
WEIGHT—(Continued)

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.20	26.40	26.53	26.66	26.80	26.93	27.06	27.19	27.32	27.46	27.59	.20
.21	27.72	27.85	27.98	28.12	28.25	28.38	28.51	28.64	28.78	28.91	.21
.22	29.04	29.17	29.30	29.44	29.57	29.70	29.83	29.96	30.10	30.23	.22
.23	30.36	30.49	30.62	30.76	30.89	31.02	31.15	31.28	31.42	31.55	.23
.24	31.68	31.81	31.94	32.08	32.21	32.34	32.47	32.60	32.74	32.87	.24
.25	33.00	33.13	33.26	33.40	33.53	33.66	33.79	33.92	34.06	34.19	.25
.26	34.32	34.45	34.58	34.72	34.85	34.98	35.11	35.24	35.38	35.51	.26
.27	35.64	35.77	35.90	36.04	36.17	36.30	36.43	36.56	36.70	36.83	.27
.28	36.96	37.09	37.22	37.36	37.49	37.62	37.75	37.88	38.02	38.15	.28
.29	38.28	38.41	38.54	38.68	38.81	38.94	39.07	39.20	39.34	39.47	.29
.30	39.60	39.73	39.86	40.00	40.13	40.26	40.39	40.52	40.66	40.79	.30
.31	40.92	41.05	41.18	41.32	41.45	41.58	41.71	41.84	41.98	42.11	.31
.32	42.24	42.37	42.50	42.64	42.77	42.90	43.03	43.16	43.30	43.43	.32
.33	43.56	43.69	43.82	43.96	44.09	44.22	44.35	44.48	44.62	44.75	.33
.34	44.88	45.01	45.14	45.28	45.41	45.54	45.67	45.80	45.94	46.07	.34
.35	46.20	46.33	46.46	46.60	46.73	46.86	46.99	47.12	47.26	47.39	.35
.36	47.52	47.65	47.78	47.92	48.05	48.18	48.21	48.44	48.58	48.71	.36
.37	48.84	48.97	49.10	49.24	49.37	49.50	49.63	49.76	49.90	50.03	.37
.38	50.16	50.29	50.42	50.56	50.69	50.82	50.95	51.08	51.22	51.35	.38
.39	51.48	51.61	51.74	51.88	52.01	52.14	52.27	52.40	52.54	52.67	.39

**MAGNESIUM ORTHOSILICATE (FORSTERITE),  $2\text{MgO} \cdot \text{SiO}_2$ . MOLECULAR WEIGHT, 140**

(Unit of calculation is one-half molecular number of  $\text{MgO}$ )

Mol	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.14	.28	.42	.56	.70	.84	.98	1.12	1.26	.00
.01	1.40	1.54	1.68	1.82	1.96	2.10	2.24	2.38	2.52	2.66	.01
.02	2.80	2.94	3.08	3.22	3.36	3.50	3.64	3.78	3.92	4.06	.02
.03	4.20	4.34	4.48	4.62	4.76	4.90	5.04	5.18	5.32	5.46	.03
.04	5.60	5.74	5.88	6.02	6.16	6.30	6.44	6.58	6.72	6.86	.04
.05	7.00	7.14	7.28	7.42	7.56	7.70	7.84	7.98	8.12	8.26	.05
.06	8.40	8.54	8.68	8.82	8.96	9.10	9.24	9.38	9.52	9.66	.06
.07	9.80	9.94	10.08	10.22	10.36	10.50	10.64	10.78	10.92	11.06	.07
.08	11.20	11.34	11.48	11.62	11.76	11.90	12.04	12.18	12.32	12.46	.08
.09	12.60	12.74	12.88	13.02	13.16	13.30	13.44	13.58	13.72	13.86	.09
.10	14.00	14.14	14.28	14.42	14.56	14.70	14.84	14.98	15.12	15.26	.10
.11	15.40	15.54	15.68	15.82	15.96	16.10	16.24	16.38	16.52	16.66	.11
.12	16.80	16.94	17.08	17.22	17.36	17.50	17.64	17.78	17.92	18.06	.12
.13	18.20	18.34	18.48	18.62	18.76	18.90	19.04	19.18	19.32	19.46	.13
.14	19.60	19.74	19.88	20.02	20.16	20.30	20.44	20.58	20.72	20.86	.14
.15	21.00	21.14	21.28	21.42	21.56	21.70	21.84	21.98	22.12	22.26	.15
.16	22.40	22.54	22.68	22.82	22.96	23.10	23.24	23.38	23.52	23.66	.16
.17	23.80	23.94	24.08	24.22	24.36	24.50	24.64	24.78	24.92	25.06	.17
.18	25.20	25.34	25.48	25.62	25.76	25.90	26.04	26.18	26.32	26.46	.18
.19	26.60	26.74	26.88	27.02	27.16	27.30	27.44	27.58	27.72	27.86	.19

MAGNESIUM ORTHOSILICATE (FORSTERITE),  $2\text{MgO} \cdot \text{SiO}_2$ . MOLECULAR WEIGHT, 140—(*Continued*)

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.20	28.00	28.14	28.28	28.42	28.56	28.70	28.84	28.98	29.12	29.26	.20
.21	29.40	29.54	29.68	29.82	29.96	30.10	30.24	30.38	30.52	30.66	.21
.22	30.80	30.94	31.08	31.22	31.36	31.50	31.64	31.78	31.92	32.06	.22
.23	32.20	32.34	32.48	32.62	32.76	32.90	33.04	33.18	33.32	33.46	.23
.24	33.60	33.74	33.88	34.02	34.16	34.30	34.44	34.58	34.72	34.86	.24
.25	35.00	35.14	35.28	35.42	35.56	35.70	35.84	35.98	36.12	36.26	.25
.26	36.40	36.54	36.68	36.82	36.96	37.10	37.24	37.38	37.52	37.66	.26
.27	37.80	37.94	38.08	38.22	38.36	38.50	38.64	38.78	38.92	39.06	.27
.28	39.20	39.34	39.48	39.62	39.76	39.90	40.04	40.18	40.32	40.46	.28
.29	40.60	40.74	40.88	41.02	41.16	41.30	41.44	41.58	41.72	41.86	.29
.30	42.00	42.14	42.28	42.42	42.56	42.70	42.84	42.98	43.12	43.26	.30
.31	43.40	43.54	43.68	43.82	43.96	44.10	44.24	44.38	44.52	44.66	.31
.32	44.80	44.94	45.08	45.22	45.36	45.50	45.64	45.78	45.92	46.06	.32
.33	46.20	46.34	46.48	46.62	46.76	46.90	47.04	47.18	47.32	47.46	.33
.34	47.60	47.74	47.88	48.02	48.16	48.30	48.44	48.58	48.72	48.86	.34
.35	49.00	49.14	49.28	49.42	49.56	49.70	49.84	49.98	50.12	50.26	.35
.36	50.40	50.54	50.68	50.82	50.96	51.10	51.24	51.38	51.52	51.66	.36
.37	51.80	51.94	52.08	52.22	52.36	52.50	52.64	52.78	52.92	53.06	.37
.38	53.20	53.34	53.48	53.62	53.76	53.90	54.04	54.18	54.32	54.46	.38
.39	54.60	54.74	54.88	55.02	55.16	55.30	55.44	55.58	55.72	55.86	.39



**IRON ORTHOSILICATE (FAYALITE),  $2\text{FeO} \cdot \text{SiO}_2$ .**  
**MOLECULAR WEIGHT, 204**

(Unit of calculation is one-half molecular number of FeO)

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.20	.41	.61	.82	1.02	1.22	1.43	1.63	1.84	.00
.01	2.04	2.24	2.45	2.65	2.86	3.06	3.26	3.47	3.67	3.88	.01
.02	4.08	4.28	4.49	4.69	4.90	5.10	5.30	5.51	5.71	5.92	.02
.03	6.12	6.32	6.53	6.73	6.94	7.14	7.34	7.55	7.75	7.96	.03
.04	8.16	8.36	8.57	8.77	8.98	9.18	9.38	9.59	9.79	10.00	.04
.05	10.20	10.40	10.61	10.81	11.02	11.22	11.42	11.63	11.83	12.04	.05
.06	12.24	12.44	12.65	12.85	13.06	13.26	13.46	13.67	13.87	14.08	.06
.07	14.28	14.48	14.69	14.89	15.10	15.30	15.50	15.71	15.91	16.12	.07
.08	16.32	16.52	16.72	16.93	17.14	17.34	17.54	17.75	17.95	18.16	.08
.09	18.36	18.56	18.77	18.97	19.18	19.38	19.58	19.79	19.99	20.20	.09
.10	20.40	20.60	20.81	21.01	21.22	21.42	21.62	21.83	22.03	22.24	.10
.11	22.44	22.64	22.85	23.05	23.26	23.46	23.66	23.87	24.07	24.28	.11
.12	24.48	24.68	24.89	25.09	25.30	25.50	25.70	25.91	26.11	26.32	.12
.13	26.52	26.72	26.93	27.13	27.34	27.54	27.74	27.95	28.15	28.36	.13
.14	28.56	28.76	28.97	29.17	29.38	29.58	29.78	29.99	30.19	30.40	.14
.15	30.60	30.80	31.01	31.21	31.42	31.62	31.82	32.03	32.23	32.44	.15
.16	32.64	32.84	33.05	33.25	33.46	33.66	33.86	34.07	34.27	34.48	.16
.17	34.68	34.88	35.11	35.31	35.50	35.70	35.90	36.11	36.31	36.52	.17
.18	36.72	36.92	37.15	37.35	37.54	37.74	37.94	38.15	38.35	38.56	.18
.19	38.76	38.96	39.19	39.39	39.58	39.78	39.98	40.19	40.39	40.60	.19

ACKERMANITE,  $3\text{CaO} \cdot 2\text{SiO}_2$ . MOLECULAR WEIGHT  
288

(Unit of calculation is one-third molecular number of  $\text{CaO}$ ).

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.29	.58	.86	1.15	1.44	1.73	2.02	2.30	2.59	.00
.01	2.88	3.17	3.46	3.74	4.03	4.32	4.61	4.90	5.18	5.47	.01
.02	5.76	6.05	6.34	6.62	6.91	7.20	7.49	7.78	8.06	8.35	.02
.03	8.64	8.93	9.22	9.50	9.79	10.08	10.37	10.66	10.94	11.23	.03
.04	11.52	11.81	12.10	12.38	12.67	12.96	13.25	13.54	13.82	14.11	.04
.05	14.40	14.69	14.98	15.26	15.55	15.84	16.13	16.42	16.70	16.99	.05
.06	17.28	17.57	17.86	18.14	18.43	18.72	19.01	19.30	19.58	19.87	.06
.07	20.16	20.45	20.74	21.02	21.31	21.60	21.89	22.18	22.46	22.75	.07
.08	23.04	23.33	23.62	23.90	24.19	24.48	24.77	25.06	25.34	25.63	.08
.09	25.92	26.21	26.50	26.78	27.07	27.36	27.65	27.94	28.22	28.51	.09

MAGNETITE,  $\text{FeO} \cdot \text{Fe}_2\text{O}_3$ . MOLECULAR WEIGHT, 232

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.23	.46	.70	.93	1.16	1.39	1.62	1.86	2.09	.00
.01	2.32	2.55	2.78	3.02	3.25	3.48	3.71	3.94	4.18	4.41	.01
.02	4.64	4.87	5.10	5.34	5.57	5.80	6.03	6.26	6.50	6.73	.02
.03	6.96	7.19	7.42	7.66	7.89	8.12	8.35	8.58	8.82	9.05	.03
.04	9.28	9.51	9.74	9.98	10.21	10.44	10.67	10.90	11.14	11.37	.04
.05	11.60	11.83	12.06	12.30	12.53	12.76	12.99	13.22	13.46	13.69	.05
.06	13.92	14.15	14.38	14.62	14.85	15.08	15.31	15.54	15.78	16.01	.06
.07	16.24	16.47	16.70	16.94	17.17	17.40	17.63	17.86	18.10	18.33	.07
.08	18.56	18.79	19.02	19.26	19.49	19.72	19.95	20.18	20.42	20.65	.08
.09	20.88	21.11	21.34	21.58	21.81	22.04	22.27	22.50	22.74	22.97	.09

ILMENITE,  $\text{FeO} \cdot \text{TiO}_2$ . MOLECULAR WEIGHT, 152

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.15	.30	.46	.61	.76	.91	1.06	1.22	1.37	.00
.01	1.52	1.67	1.82	1.98	2.13	2.28	2.43	2.58	2.74	2.89	.01
.02	3.04	3.19	3.34	3.50	3.65	3.80	3.95	4.10	4.26	4.41	.02
.03	4.56	4.71	4.86	5.02	5.17	5.32	5.47	5.62	5.78	5.93	.03
.04	6.08	6.23	6.38	6.54	6.69	6.84	6.99	7.14	7.30	7.45	.04
.05	7.60	7.75	7.90	8.06	8.21	8.36	8.51	8.66	8.82	8.97	.05
.06	9.12	9.27	9.42	9.58	9.73	9.88	10.03	10.18	10.34	10.49	.06
.07	10.64	10.79	10.94	11.10	11.25	11.40	11.55	11.70	11.86	12.01	.07
.08	12.16	12.31	12.46	12.62	12.77	12.92	13.07	13.22	13.38	13.53	.08
.09	13.68	13.83	13.98	14.14	14.29	14.44	14.59	14.74	14.90	15.05	.09

HEMATITE,  $\text{Fe}_2\text{O}_3$ . MOLECULAR WEIGHT, 160

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.16	.32	.48	.64	.80	.96	1.12	1.28	1.44	.00
.01	1.60	1.76	1.92	2.08	2.24	2.40	2.56	2.72	2.88	3.04	.01
.02	3.20	3.36	3.52	3.68	3.84	4.00	4.16	4.32	4.48	4.64	.02
.03	4.80	4.96	5.12	5.28	5.44	5.60	5.76	5.92	6.08	6.24	.03
.04	6.40	6.56	6.72	6.88	7.04	7.20	7.36	7.52	7.68	7.84	.04

APATITE,  $3\text{CaO} \cdot \text{P}_2\text{O}_5 + \frac{\text{CaF}_2}{3}$ . MOLECULAR WEIGHT, 336(Unit of calculation is molecular number of  $\text{P}_2\text{O}_5$ )

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.34	.67	1.01	1.34	1.68	2.02	2.35	2.69	3.02	.00
.01	3.36	3.70	4.03	4.37	4.70	5.04	5.38	5.71	6.05	6.38	.01
.02	6.72	7.06	7.39	7.73	8.06	8.40	8.74	9.07	9.41	9.74	.02
.03	10.08	10.42	10.75	11.09	11.42	11.76	12.10	12.43	12.77	13.10	.03
.04	13.44	13.78	14.11	14.45	14.78	15.12	15.46	15.79	16.13	16.46	.04

ACMITE,  $\text{Na}_2\text{O} \cdot \text{Fe}_2\text{O}_3 \cdot 4\text{SiO}_2$ . MOLECULAR WEIGHT, 462

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.46	.92	1.39	1.85	2.31	2.77	3.23	3.70	4.16	.00
.01	4.62	5.08	5.54	6.01	6.47	6.93	7.39	7.85	8.32	8.78	.01
.02	9.24	9.70	10.16	10.63	11.09	11.55	12.01	12.47	12.94	13.40	.02
.03	13.86	14.32	14.78	15.25	15.71	16.17	16.63	17.09	17.56	18.02	.03
.04	18.48	18.94	19.40	19.87	20.33	20.79	21.25	21.71	22.18	22.64	.04
.05	23.10	23.56	24.02	24.49	24.95	25.41	25.87	26.33	26.80	27.26	.05
.06	27.72	28.18	28.64	29.11	29.57	30.03	30.49	30.95	31.42	31.88	.06
.07	32.34	32.80	33.26	33.73	34.19	34.65	35.11	35.57	36.04	36.50	.07
.08	36.96	37.42	37.88	38.35	38.81	39.27	39.73	40.19	40.66	41.12	.08
.09	41.58	42.04	42.50	42.97	43.43	43.89	44.35	44.81	45.28	45.74	.09

SODIUM METASILICATE,  $\text{Na}_2\text{O} \cdot \text{SiO}_2$ . MOLECULAR  
WEIGHT, 122

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.12	.24	.37	.49	.61	.73	.85	.98	1.10	.00
.01	1.22	1.34	1.46	1.59	1.71	1.83	1.95	2.07	2.20	2.32	.01
.02	2.44	2.56	2.68	2.81	2.93	3.05	3.17	3.29	3.42	3.54	.02
.03	3.66	3.78	3.90	4.03	4.15	4.27	4.39	4.51	4.64	4.76	.03
.04	4.88	5.00	5.12	5.25	5.37	5.49	5.61	5.73	5.86	5.98	.04
.05	6.10	6.22	6.34	6.47	6.59	6.71	6.83	6.95	7.08	7.20	.05
.06	7.32	7.44	7.56	7.69	7.81	7.93	8.05	8.17	8.30	8.42	.06
.07	8.54	8.66	8.78	8.91	9.03	9.15	9.27	9.39	9.52	9.64	.07
.08	9.76	9.88	10.00	10.13	10.25	10.37	10.49	10.61	10.74	10.86	.08
.09	10.98	11.10	11.22	11.35	11.47	11.59	11.71	11.83	11.96	12.08	.09

PEROVSKITE,  $\text{CaO} \cdot \text{TiO}_2$ . MOLECULAR WEIGHT, 136

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.14	.27	.41	.54	.68	.82	.95	1.09	1.22	.00
.01	1.36	1.50	1.63	1.77	1.90	2.04	2.18	2.31	2.45	2.58	.01
.02	2.72	2.86	2.99	3.13	3.26	3.40	3.54	3.67	3.81	3.94	.02
.03	4.08	4.22	4.35	4.49	4.62	4.76	4.90	5.03	5.17	5.30	.03
.04	5.44	5.58	5.71	5.85	5.98	6.12	6.26	6.39	6.53	6.66	.04
.05	6.80	6.94	7.07	7.21	7.34	7.48	7.62	7.75	7.89	8.02	.05
.06	8.16	8.30	8.43	8.57	8.70	8.84	8.98	9.11	9.25	9.38	.06
.07	9.52	9.66	9.79	9.93	10.06	10.20	10.34	10.47	10.61	10.74	.07
.08	10.88	11.02	11.15	11.29	11.42	11.56	11.70	11.83	11.97	12.10	.08
.09	12.24	12.38	12.51	12.65	12.78	12.92	13.06	13.19	13.33	13.46	.09

TITANITE,  $\text{CaO} \cdot \text{TiO}_2 \cdot \text{SiO}_2$ . MOLECULAR WEIGHT,  
196

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.20	.39	.59	.78	.98	1.18	1.37	1.57	1.76	.00
.01	1.96	2.16	2.35	2.55	2.74	2.94	3.14	3.33	3.53	3.72	.01
.02	3.92	4.12	4.31	4.51	4.70	4.90	5.10	5.29	5.49	5.68	.02
.03	5.88	6.08	6.27	6.47	6.66	6.86	7.06	7.25	7.45	7.64	.03
.04	7.84	8.04	8.23	8.43	8.62	8.82	9.02	9.21	9.41	9.60	.04
.05	9.80	10.00	10.19	10.39	10.58	10.78	10.98	11.17	11.37	11.56	.05
.06	11.76	11.96	12.15	12.35	12.54	12.74	12.94	13.13	13.33	13.52	.06
.07	13.72	13.92	14.11	14.31	14.50	14.70	14.90	15.09	15.29	15.48	.07
.08	15.68	15.88	16.07	16.27	16.46	16.66	16.86	17.05	17.25	17.44	.08
.09	17.64	17.84	18.03	18.23	18.42	18.62	18.82	19.01	19.21	19.40	.09

FLUORITE,  $\text{CaF}_2$ . MOLECULAR WEIGHT, 78

Mol.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009	Mol.
.00	.00	.07	.16	.23	.31	.39	.47	.55	.62	.70	.00
.01	.78	.86	.94	1.01	1.09	1.17	1.25	1.33	1.40	1.48	.01
.02	1.56	1.64	1.72	1.79	1.87	1.95	2.03	2.11	2.18	2.26	.02
.03	2.34	2.42	2.50	2.57	2.65	2.73	2.81	2.89	2.96	3.04	.03
.04	3.12	3.20	3.28	3.35	3.43	3.51	3.59	3.67	3.74	3.82	.04
.05	3.90	3.98	4.06	4.13	4.21	4.29	4.37	4.45	4.52	4.60	.05
.06	4.68	4.76	4.84	4.91	4.99	5.07	5.15	5.23	5.30	5.38	.06
.07	5.46	5.54	5.62	5.69	5.77	5.85	5.93	6.01	6.08	6.16	.07
.08	6.24	6.32	6.40	6.47	6.55	6.63	6.71	6.79	6.86	6.94	.08
.09	7.02	7.10	7.18	7.25	7.33	7.41	7.49	7.57	7.64	7.72	.09













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